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Electrical Actuation Technology Bridging

Proceedings of a workshop held in Huntsville, Alabama September 29–October 1, 1992

NASA

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Electrical Actuation Technology Bridging

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Proceedings of a workshop sponsored by NASA Headquarters, Office of Space Systems Development and the George C. Marshall Space Flight Center, and held in Huntsville, Alabama, September 29–October 1, 1992

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Preface

This document contains the proceedings of the NASA Electrical Actuation Technology Bridging (ELA-TB) Workshop held in Huntsville, Alabama, September 29–October 1, 1992. The workshop was sponsored by NASA Office of Space Systems Development and Marshall Space Flight Center (MSFC). The workshop addressed key technologies bridging the entire field of electrical actuation including systems methodology, control electronics, power source systems, reliability, maintainability, and vehicle health management with special emphasis on thrust vector control (TVC) applications on NASA launch vehicles. Speakers were drawn primarily from industry with participation from universities and government. In addition, prototype hardware demonstrations were held at the MSFC Propulsion Laboratory each afternoon. Splinter sessions held on the final day afforded participants the opportunity to discuss key issues and to provide overall recommendations. All presentations are included in this document.

The workshop organizers express their appreciation to the session chairmen, speakers, and participants, whose efforts contributed to the technical excellence of the workshop.

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[1]Presentation not available.
[2]Paper presented in Session V on agenda.

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[3]Paper presented in Session IX on agenda.

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[4]Paper presented in Session V on agenda.

Summary of the Electrical Actuation - Technology Bridging Workshop

The 1992 Electrical Actuation (ELA) - Technology Bridging Workshop was held at the Radisson Suite Hotel in Huntsville, Alabama, September 29 - October 1, 1992. This workshop was sponsored by NASA Headquarters/Code DD and hosted by the Component Development Division of the Propulsion Laboratory at the Marshall Space Flight Center. The workshop addressed key technology issues in the field of electromechanical actuation including system design, control electronics, power source systems, vehicle health monitoring, reliability, and maintainability, with special emphasis on thrust vector control (TVC) applications on NASA launch vehicles. In addition, the workshop provided the opportunity for discussion of near-term power source developments and ELA system requirements between the ELA systems and the power source communities.

Approximately 150 individuals from both government and industry participated in the workshop. Attendance is listed starting on page 3. The final workshop agenda is listed starting on page 11.

One of the more productive outputs of the workshop resulted from the splinter sessions. These sessions afforded participants the opportunity to discuss key issues and to provide overall recommendations. Most frequently emphasized was the need for detailed requirements for actuator, power source, and control electronics. These requirements are essential to perform detailed system trade studies in order to meet the critical element of a hot fire test on the SSME Technology Test Bed (TTB). A listing of suggested topics provided to each splinter session group, along with a summary output from each group, is provided starting on page 1.

Hardware demonstrations were held at the MSFC Propulsion Laboratory each afternoon of the workshop. Basic performance criteria were demonstrated by the following:

- Boeing/Allied Signal EHA TVC Prototype
- Honeywell Prototype Redundant TVC and Health Management
- LeRC/GDSS Induction Motor Prototype TVC
- MSFC Prototype TVC Actuator
- Boeing Turbo-Alternator
- Moog Prototype TVC Actuator
- MSFC and Textron SSME Propellant Control Valve Actuator

The GHe turbo-alternator was developed by Boeing and Allied Signal under the JPO-ADP Program. The primary objective for this program was to demonstrate a helium driven turbo-alternator suitable for powering electrically driven thrust vector control actuators. The hardware consisted of a single stage axial impulse turbine directly driving a 50 kW 2-pole toothless

permanent magnet alternator. The power conversion and control scheme used was a 3-phase rectified bridge and speed control loop for adjusting alternator output. The electrical power quality objective for this equipment was a modified version of MIL-STD-704 desired to minimize corona effects during launch vehicle operation. The upper transient value of 2730 was imposed for that reason, and a nominal bus voltage of 220 volts was selected. The GHe turbo-alternator was demonstrated successfully under a multitude of no load and full load conditions and is currently completing tests at Allied Signal's AiResearch Division.

The electromechanical actuator (EMA) developed under contract by HR Textron is to replace the hydraulic main oxidizer valve (MOV) on the space shuttle main engine (SSME). The unit was delivered to MSFC one week prior to the workshop; as a result, no test data was presented other than acceptance test performed at HR Textron. The plans for this EMA for the next year or year and one-half encompass characterization tests, vibration, shock EMI, EMC, flow tests, and flight simulation laboratory (FSL) tests. The summation of these tests assure that the EMA meets the requirements imposed on the hydraulic MOV actuator and qualifies it to go to Technology Test Bed for an engine hot fire test.

A table of TVC prototype hardware comparisons is found on page xvii, along with color photocopies of the demonstrated hardware.

The general consensus of the workshop was that ELA technology has been demonstrated to be feasible for SSME/STME class TVC systems, as shown by the performance capabilities of the workshop prototype hardware. However, an overall strategy towards transferring this technology to a flight program, along with the development of several key tools, is still undefined. Specific requirements must also be provided in order to focus the ELA program. Recommendations were made to hold a power source Technical Interchange Meeting (TIM) within 6 months at Kennedy Space Center. The next ELA workshop was recommended to be held no sooner than 12 months from now, focusing on full-power TVC/ELA demonstrations with redundancy management capabilities.

Proceedings from the 1992 ELA Technology Bridging Workshop are being distributed with a video summary of the prototype hardware demonstrations. The successful completion of this workshop represents a major milestone in the development of ELA systems for TVC applications. The support of NASA Headquarters/Code DD in achieving this success is gratefully acknowledged.

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NASA ELECTRICAL ACTUATION TECHNOLOGY BRIDGING WORKSHOP
MARSHALL SPACE FLIGHT CENTER

AGENDA
FOR
TUESDAY, SEPTEMBER 29, 1992

7:40	**Check-in**	
8:00	**Session I. ELA Program Overviews**	Chairman: Charles Cornelius/MSFC
	1. NASA HQ Perspective	Paul Herr/Code DD
	2. KSC/STS Hydraulic Operations	Carey McCleskey/KSC
	3. ELA-TB Program Overview	Gale Sundberg/LeRC
9:15	**Break**	
	4. NLS Keynote Speaker	Rick Bachtel/MSFC
	5. DOD ELA Program Overview	David Homan/DOD
10:00	**Session II. ELA Systems Methodology**	Chairman: John Harbison/MSFC
	1. EMA Avionics Design Methodology	Jim Mildice/GDSS
	2. EHA Design Methodology	John Anderson/Boeing
11:00	**Lunch**	
12:00	**Session III. ELA Control Electronics**	Chairman: David Howard/MSFC
	1. DC Motor Control Electronics	Justino Montenegro/MSFC
	2. AC Induction Motor Control Electronics	Ken Schreiner/GDSS
	3. DC Motor Micro-Controller Design	Collin Hugget/Allied Signal
	4. TVC Engine Start Transient Response	Jeff Ring/Honeywell
1:30	**Session IV. ELA Prototype Designs & Test Results**	Chairman: Monica Hammond/MSFC
	1. Boeing/Allied Signal - EHA TVC Prototype	
	2. Honeywell Prototype Redundant TVC and Health Management	
2:30	**Session V. ELA HARDWARE DEMONSTRATIONS**	

	<u>Group I</u>	<u>Group II</u>	<u>Group III</u>
2:45	Depart Radisson	EMA Motor/Gear Optimization - George Doane/UAH	
3:00	Boeing/ASAC Demo	Propellant Control Valve EMA & BIT - Matt Lister/Aerojet	
3:20	Honeywell Demo	Depart Radisson	Depart Radisson
3:45	Depart MSFC	Boeing/ASAC Demo	Space Station Tour
4:05	Open	Honeywell Demo	Space Station Tour (con't)
4:25	Open	Depart MSFC	Boeing/ASAC Demo
4:45	Open	Open	Honeywell Demo
5:05	Open	Open	Depart MSFC

5:15 **Close of Business**

NASA ELECTRICAL ACTUATION TECHNOLOGY BRIDGING WORKSHOP
MARSHALL SPACE FLIGHT CENTER

AGENDA
FOR
WEDNESDAY, SEPTEMBER 30, 1992

7:40	**Check-in**	
8:00	**Session VI. ELA Power Source Systems**	Chairman: David Hall/MSFC
	1. Bipolar Lead-Acid Batteries	Doug Pierce/Johnson Controls
	2. Silver Zinc Batteries	Curtis Brown/Eagle-Picher
	3. Bipolar Lithium Batteries	Franz Goebel/Yardney
	4. Advanced Flywheel Technology	David Eisenhauer/SatCon
9:30	**Break**	
	5. Turbo-Alternators	Cliff Jacobs/Sundstrand
	6. NLS GH2 Turbo-Alternator	John Anderson/Boeing
	7. ELA Power Source Simulators	Mike Bradway/LESC
10:45	**Session VII. ELA Operations**	Chairman: Carey McCleskey
	1. ELA Operations Test Bed	Carey McCleskey/KSC
	2. Cryogenic Ground Support Applications	Bill St. Cyr/SSC
	3. High Technology Test Bed	Bob Brogdon/Lockheed
12:00	**Lunch**	
1:00	**Session VIII. ELA Prototype Designs &Test Results**	Chairman: Monica Hammond/MSFC
	1. LeRC/GDSS Induction Motor Prototype TVC	
	2. MSFC TVC Prototype	
	3. Boeing Turbo-Alternator	
2:15	**Session IX. ELA HARDWARE DEMONSTRATIONS**	

	Group I	Group II	Group III
2:15	Depart Radisson	Break	Break
2:30	LeRC/GDSS Demo	ELA Gear Train, Roller & Ball Screw Components	
2:50	MSFC TVC Demo	Kurt Niederpruem/ ITW Spiroid	
3:10	Boeing Turbo-Alt.	Depart Radisson	Depart Radisson
3:30	Depart MSFC	LeRC/GDSS Demo	Technology Test Bed
3:50	Open	MSFC TVC Demo	Technology Test Bed (con't)
4:10	Open	Boeing Turbo-Alt.	Technology Test Bed (con't)
4:30	Open	Depart MSFC	LeRC/GDSS Demo
4:50	Open	Open	MSFC TVC Demo
5:10	Open	Open	Boeing Turbo-Alt.
5:20	Open	'Open	Depart MSFC

5:30 Close of Business

NASA ELECTRICAL ACTUATION TECHNOLOGY BRIDGING WORKSHOP
MARSHALL SPACE FLIGHT CENTER

AGENDA
FOR
THURSDAY, OCTOBER 1, 1992

7:40	**Check-in**	
8:00	**Session X. EMA FDIR and VHM**	Chairman: Fred Huffaker/MSFC
	1. EMA Health Management Using Smart Sensors	Jeff Schoess/Honeywell
	2. Intelligent BIT on EMA	Erv Hanson/LeRC
	3. Fault Tolerant System Test for ELA	Norm Osborn/Martin Marietta
	4. TVC FMEA and Failures in Test	Rae Ann Weir/MSFC
10:00	**Session XI. Splinter Session Assignments**	
	1. System Designs	Dave Renz/LeRC
	2. Control Electronics	Justino Montenegro/MSFC
	3. Power Source Systems	David Hall/MSFC
	4. Operations and Ground Support	Carey McCleskey/KSC
	5. Redundancy and Health Management	Don Brown/JSC
11:00	**ELA Working Lunch (Radisson Magnolia Room)**	
12:00	**Splinter Session Recommendations**	Chairman: John Sharkey/MSFC
1:00	**Session XII. ELA Prototype Design & Test Results**	Chairman: Monica Hammond/MSFC
	1. Moog Prototype TVC Actuator	
	2. MSFC & Textron SSME Propellant Control Valve Actuators	
	3. Allied Signal TVC EMA Prototype	
2:15	**Session XIII. ELA HARDWARE DEMONSTRATIONS**	

	Group I	Group II	Group III
2:15	Depart Radisson	Open	Open
2:30	Moog Demo	Open	Open
2:50	MSFC/Textron Demo	Open	Open
3:10	Allied-Signal EMA Demo	Depart Radisson	Depart Radisson
3:30	Depart MSFC	Moog Demo	Large Space Structures Tour
3:50	Open	MSFC/Textron Demo	Large Space Structures Tour
4:10	Open	Allied-Signal EMA Demo	Large Space Structures Tour
4:30	Open	Depart MSFC	Moog Demo
4:50	Open	Open	MSFC/Textron Demo
5:10	Open	Open	Allied-Signal EMA Demo
5:20	Open	Open	Depart MSFC

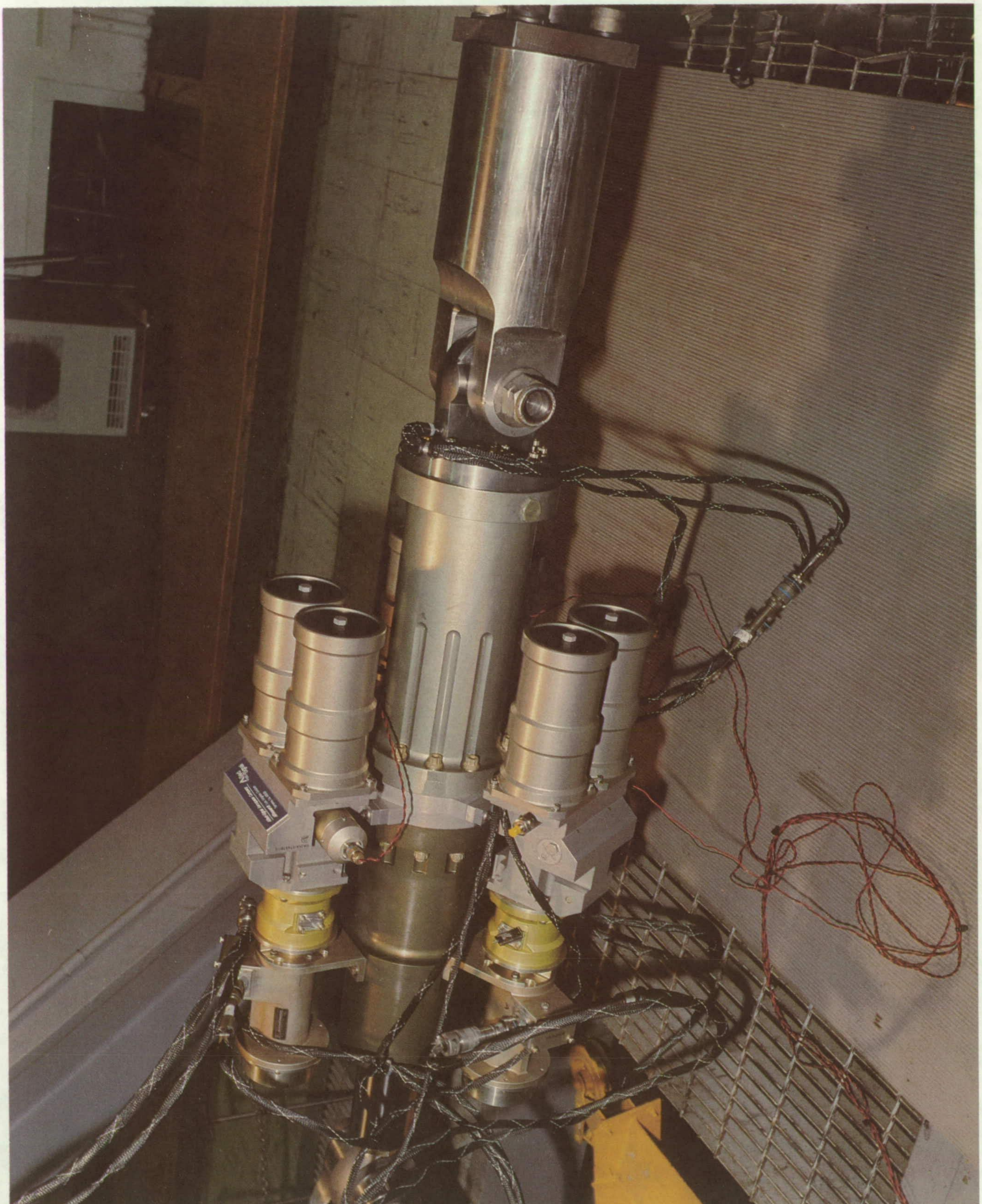
5:30 **Close of Business**

TABLE OF COMPARISONS

Designed Actuator Parameters for Workshop Prototypes

Actuator Parameters	Boeing/Allied Signal EHA TVC Prototype	Honeywell Prototype Redundant TVC	LeRC/GDSS Induction Motor Prototype TVC	MSFC Prototype TVC Actuator	Moog Prototype TVC Actuator
Force (lb)	50,000	40,000	48,000	35,000	48,000 *
Stroke (in)	11.5	14	+/- 5.4	+/- 6	+/- 5.5 *
Speed (in/sec)	3.3	12	7.4	5 *	5.2 *
Output Power (HP)	25	75	34.6	25	38
Input Power (KW)	35	70	70	27 *	30 *
Weight (lb)	300 *	230 *	300 *	380 *	337.3 *
Bandwidth (Hz)	7	4	3.2	3 *	8 *
Acceleration (in/sec^2)	180	200	52	62.81 *	60 *
Redundancy	3 *	4 *	1	1	1
Power Electronic Unit	Digital PWM	Hybrid PWM	Digital PDM	Analog PWM	Analog PWM
Cooling Required	Internal Oil	Passive	Forced Air	Passive	Passive

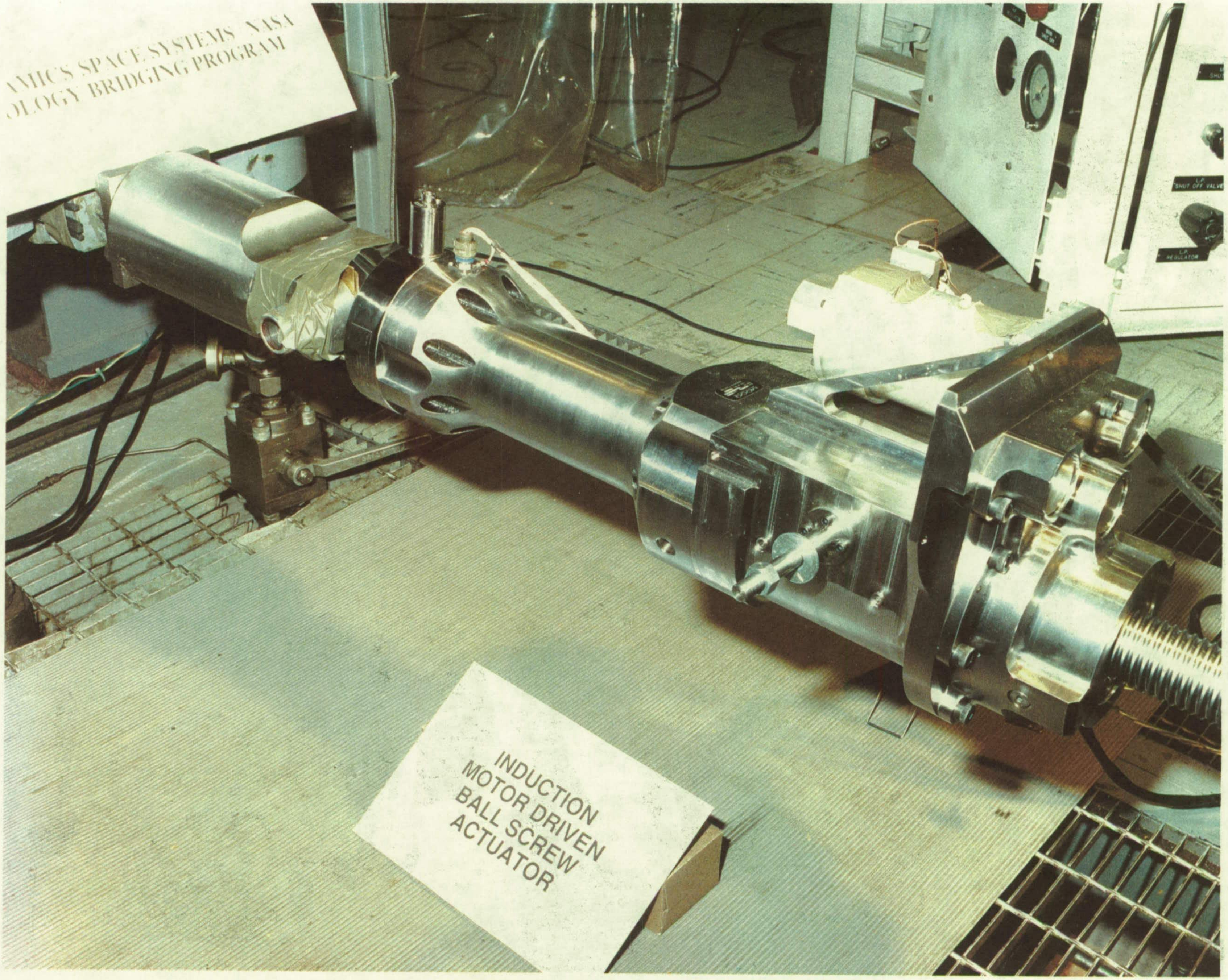
* **NOTE**: Test Verified Parameter



BOEING/ALLIED SIGNAL EHA TVC PROTOTYPE

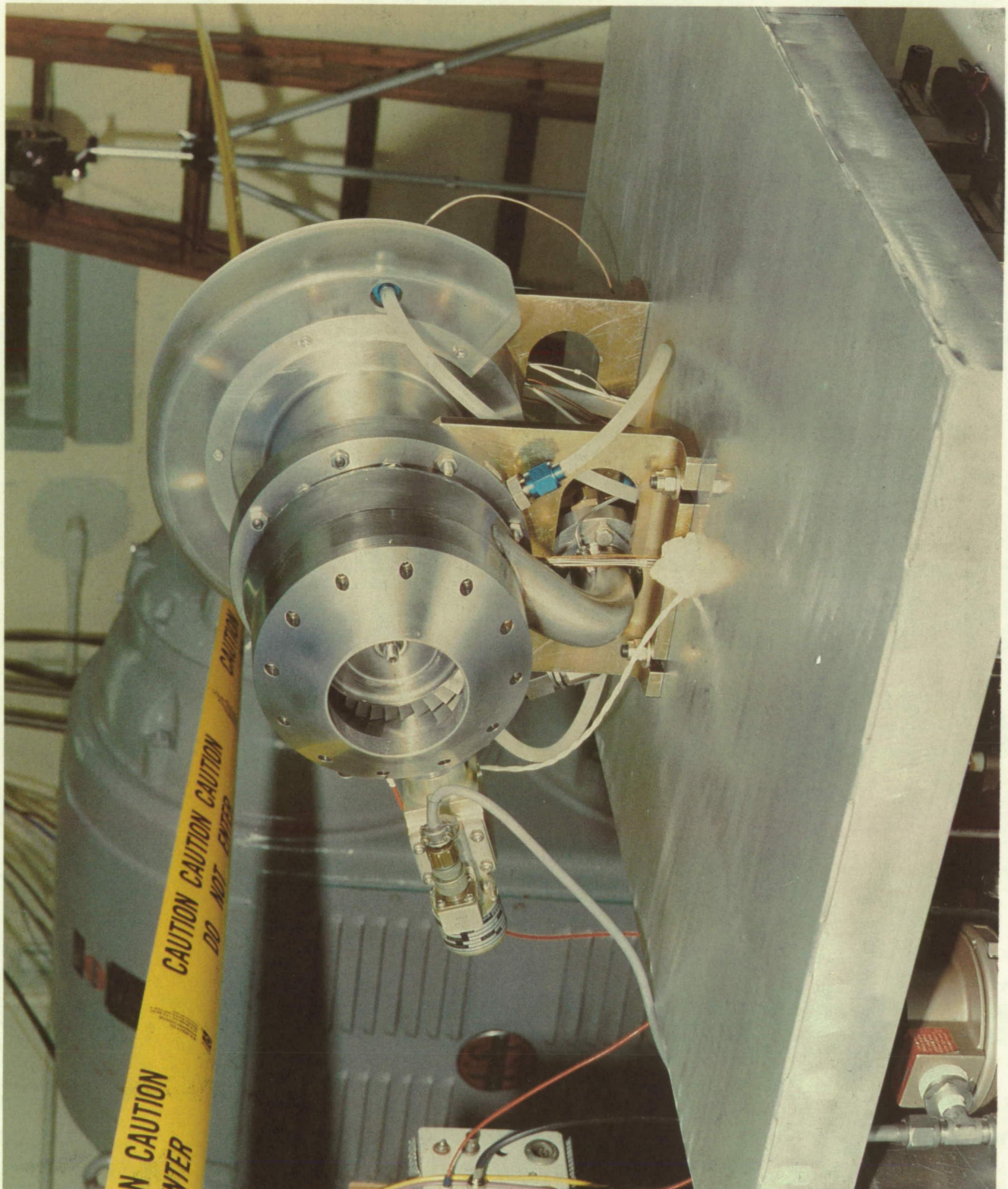
HONEYWELL PROTOTYPE REDUNDANT TVC AND HEALTH MANAGEMENT

HONEYWELL DEMONSTRATION

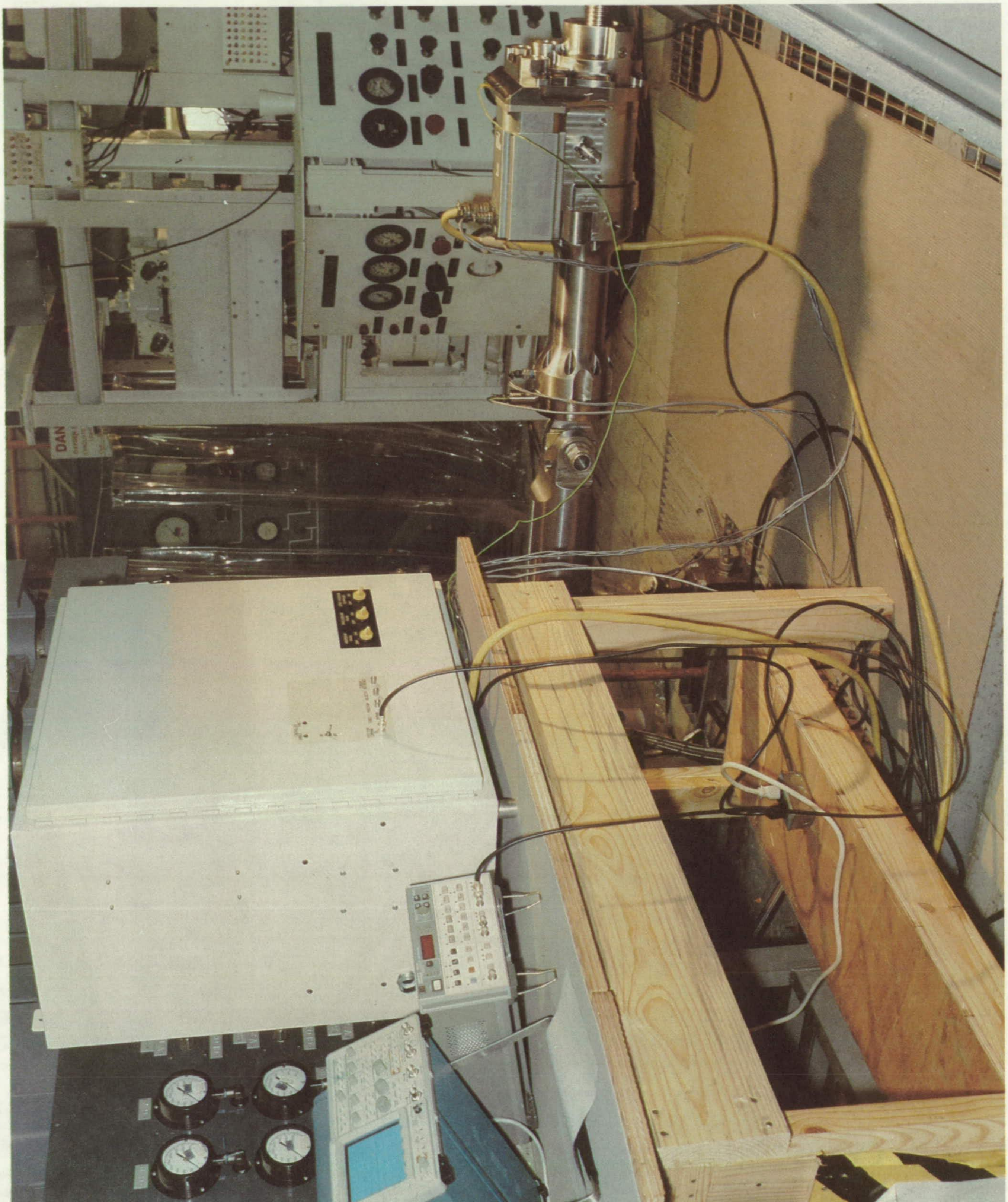


LeRC/GDSS INDUCTION MOTOR PROTOTYPE TVC

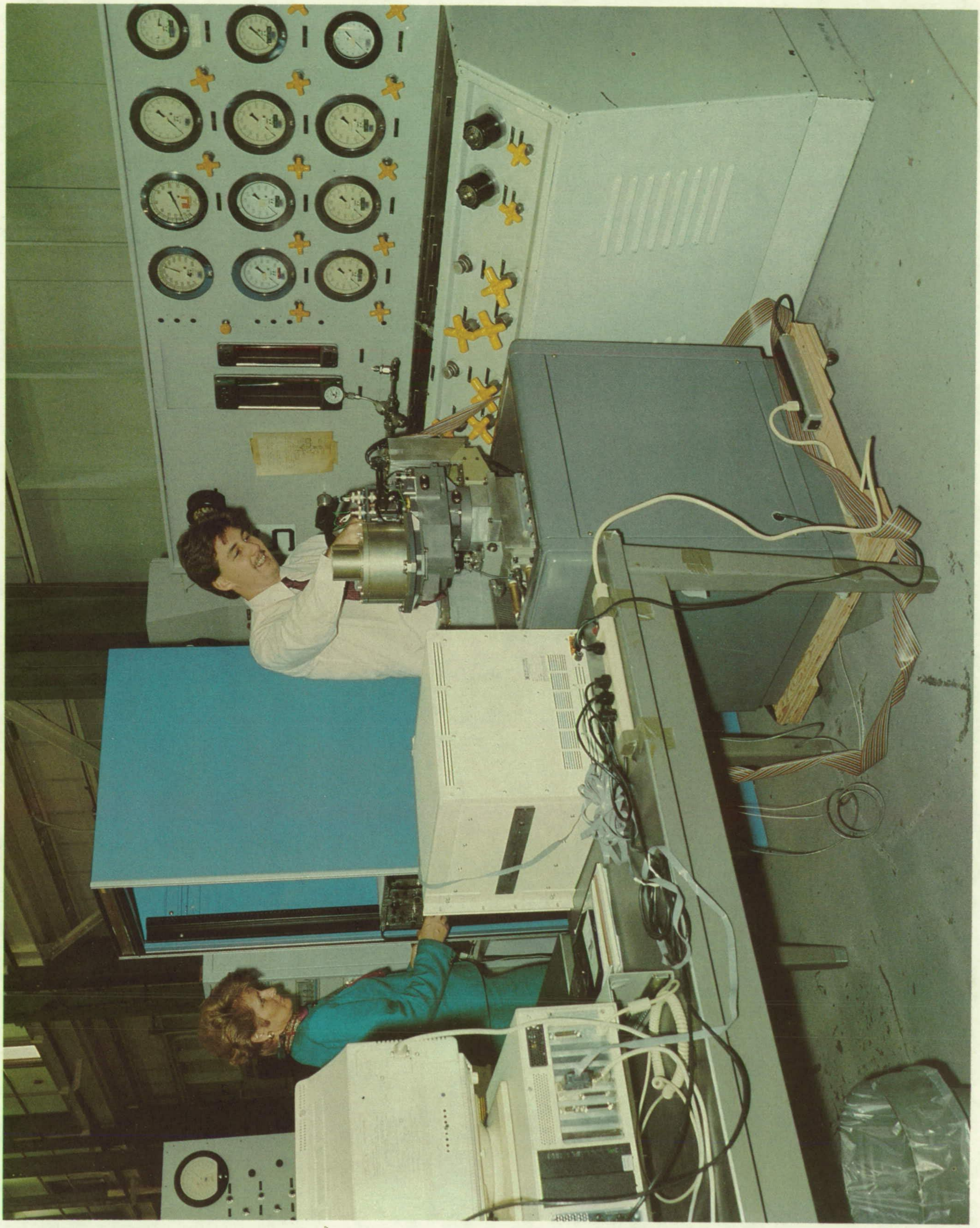
MSFC TVC PROTOTYPE



BOEING TURBO-ALTERNATOR



MOOG PROTOTYPE TVC ACTUATOR



MSFC AND TEXTRON SSME PROPELLANT CONTROL VALVE ACTUATOR

SESSION I

ELA PROGRAM OVERVIEWS

NASA

ADVANCED DEVELOPMENT BRIDGING PROGRAMS OVERVIEW

Presentation to:
NASA Electrical Actuation
Technology Bridging Workshop

September 29 - October 1, 1992
Radisson Suite Hotel
Huntsville, AL

Paul Herr
Advanced Programs Division
NASA Headquarters

ADVANCED DEVELOPMENT

Demonstrate and Apply Promising Technologies And/Or Procedures To a Level That Meets Flight Program Requirements

NASA

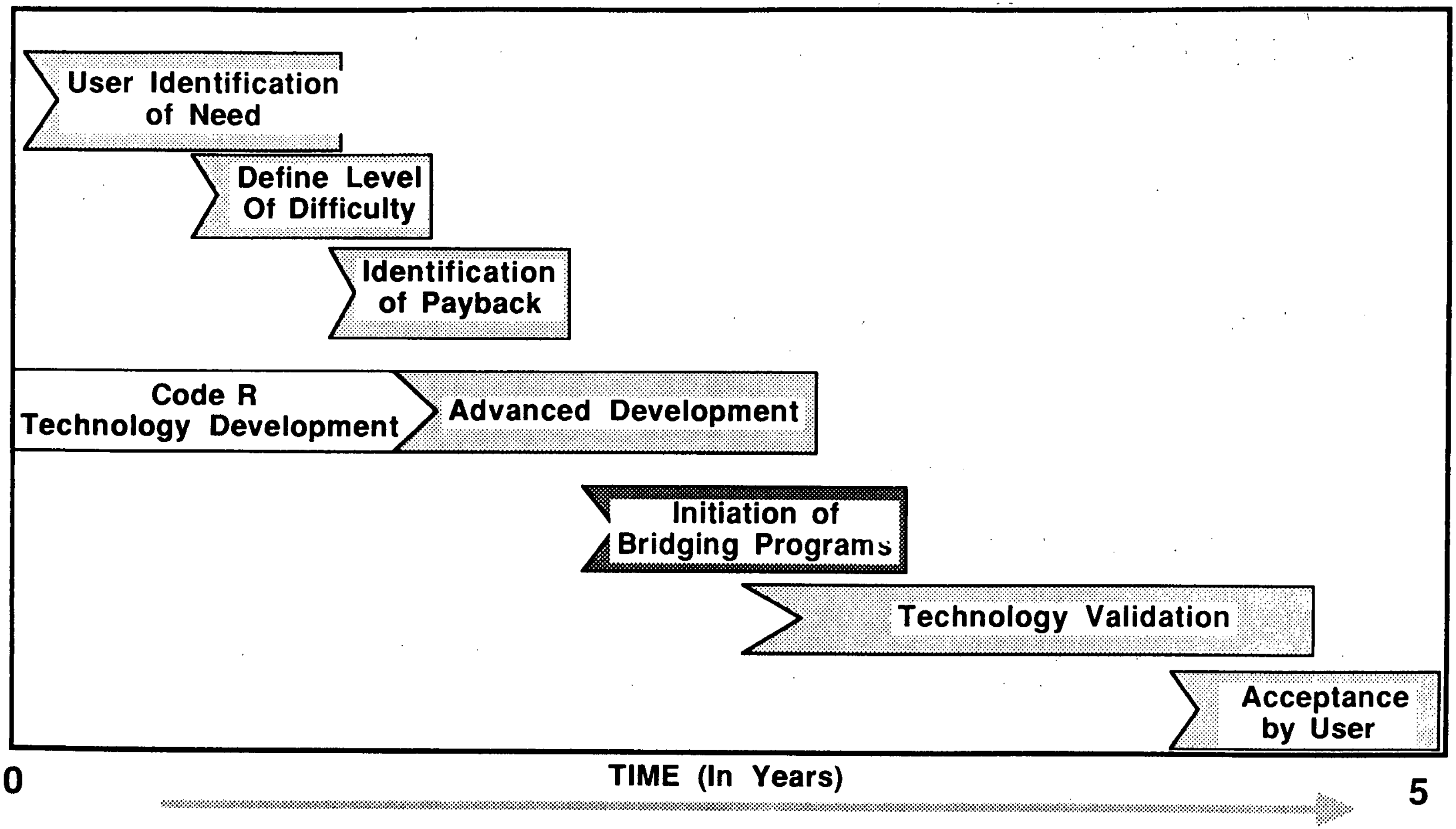
THE TECHNOLOGY MATURATION PROCESS

LEVEL	DESCRIPTION	
1.	Basic Principles Observed and Reported	TECHNOLOGY DEVELOPMENT
2.	Conceptual Design Formulated	TECHNOLOGY DEVELOPMENT
3.	Conceptual Design Tested Analytically Or Experimentally	TECHNOLOGY DEVELOPMENT
4.	Critical Function/Characteristic Demonstration	TECHNOLOGY DEVELOPMENT; ADVANCED DEVELOPMENT
5.	Component/Brassboard Tested In Relevant Environment	TECHNOLOGY DEVELOPMENT; ADVANCED DEVELOPMENT
6.	Propotype/Engineering Model Tested In Relevant Environment	ADVANCED DEVELOPMENT
7.	Engineering Model Tested In Space	ADVANCED DEVELOPMENT
8.	"Flight-Qualified" System	OPERATIONAL SYSTEMS
9.	"Flight-Proven" System	OPERATIONAL SYSTEMS

ADVANCED DEVELOPMENT

NASA

TECHNOLOGY TRANSFER/INSERTION PROCESS



TECHNOLOGY TRANSFER/INSERTION IS A PROCESS REQUIRING STRONG COMMITTMENT AND SUPPORT FROM TECHNOLOGY DEVELOPERS AND USERS

Office Of Space Systems Development

PH-910314-01-DG

NASA

ANATOMY OF BRIDGING PROGRAMS

- EACH BRIDGING TASK FOCUSED ON AN OBJECTIVE DEFINED BY USER(S)
  - Demonstration Payoff Benefits Are Defined "Before The Fact"
  - Leverages and Concentrates Limited Funds and Special Skills From Both Governemnt and Industry Toward Specific Objective(s)
- SMALL GROUP INCLUDES ONLY PARTICIPANTS/CONTRIBUTORS WITHIN PROCESS
  - Establishes A "New Way Of Doing Business"
- PRECIPITATES "CULTURAL CHANGE" WITHIN THE NASA INSTITUTIONAL INTER-CENTER, AND PROGRAM OFFICE STRUCTURE
- INCORPORATES ALL R&T CONSTITUENCIES AT INITIATION OF THE TASK
- OF THE FOUR BRIDGING PROGRAMS, THE ELA TASKS ARE HIGHLY INTEGRATED, TECHNICALLY ADVANCED AND MOST SUCCESSFUL
  - Showcase For The "Bridging Programs" Concept
  - Demonstration Model For Other Tasks To Emulate

ADVANCED DEVELOPMENT "BRIDGING PROGRAM"
Ground Rules

- PROJECT DIRECTED TO HIGH PRIORITY OSSD TECHNOLOGY NEEDS
- PROJECT DIRECTED AT SPECIFIC END POINT TECHNOLOGIES
- PROJECT SERVING AS A MECHANISM FOR TECHNOLOGY TRANSFER WITHIN NASA

BRIDGING PROGRAMS ARE "PILOT PROJECTS" WHICH PROVIDE A MECHANISM TO TRANSFER TECHNOLOGY FROM THE TECHNOLOGY DEVELOPER TO THE TECHNOLOGY USER

NASA

ADVANCED DEVELOPMENT OVERVIEW

OSSD (OSF) Technology Requirements

- DURING 1991, EARLY 1992 OSF POLLED ALL PROGRAM OFFICES (SSF, STS, ELV's, etc.) TO IDENTIFY AREA'S OF TECHNOLOGY REQUIREMENTS.

- LARGE LIST OF REQUIREMENTS WERE GROUPED & PRIORITIZED INTO 21 MAJOR CATEGORIES
  - 16 Were NASA Unique
  - 5 Were Industry Driven

- LIST OF 21 WERE PRESENTED TO OAST (Code R)
  - OAST Technology Managers Incorporated Majority Within On-going Programs

- BASED ON MULTI-APPLICATIONS AND HIGH PAYOFF POTENTIAL FOUR PILOT BRIDGING PROJECTS WERE SELECTED FOR IMPLEMENTATION
  - Three Are Now Underway (Initiated In FY91)
  - Fourth (IVHM) Selected For FY93

OSSD (OSF) Technology Requirements Evaluation

Technology Areas

	Program Unique Technologies
$\boxed{1}$	Vehicle Health Management
2	Advanced Turbomachinery Components and Models
3	Combustion Devices
4	Advanced Heat Rejection Devices
5	Water Recovery and Management
6	High Efficiency Space Power Systems
7	Advanced Extravehicular Mobility Unit Technologies
$\boxed{8}$	Electromechanical Control Systems/Electrical Actuation
9	Crew Training Systems
$\boxed{10}$	Characterization of Al-Li Alloys
11	Cryogenic Supply, Storage, and Handling
12	Thermal Protection Systems for High Temperature Applications
13	Robotic Technologies
14	Orbital Debris Protection
$\boxed{15}$	Guidance, Navigation and Control
16	Advanced Avionics Architectures
	Industry Driven Technologies
	Signal Transmission and Reception
	Advanced Avionics Software
	Video Technologies
	Environmentally Safe Cleaning Solvents, Refrigerants and Foams
	Non-Destructive Evaluation

☐ **OSSD Bridging Programs**

ADVANCED DEVELOPMENT "BRIDGING PROGRAMS"

Currently underway:

- ELECTRICAL ACTUATION (ELA)
- AUTONOMOUS GUIDANCE, NAVIGATION AND CONTROL (AGN&C)
- ALUMINUM-LITHIUM ALLOYS

Planned:

- INTEGRATED VEHICLE HEALTH MANAGEMENT (IVHM)

ELECTRICAL ACTUATION
Bridging Activities

OBJECTIVES

Develop and demonstrate a high power/high performance electromechanical actuator in primary flight control applications

PAYOFFS

- Elimination of high pressure hydraulic systems
- Elimination of central hydraulic APU's, hazardous/ toxic fluids
- Reduction of labor intensive tests, prep time, and ops. costs
- Improved dispatch reliability,operability and abort recovery
- Improved launch window (late-hold capability)
- Reduced standdown time-rapid changeout/retest

NASA

ELA BRIDGING TEAM

JSC

- Project management & integration
- Flight dynamic requirements definition
- Fault tolerance/redundancy management strategies definition

MSFC

- Thrust vector control and propulsion control valve applications

LeRC

- EMA/power component development
- EMA/power system integration development and demonstration

ELA Bridging Program

KSC

- EMA checkout and operational concepts
- Costs/benefits analysis

SSC

- Development of SSME test stand for valve application for EMA demo
- Costs/benefits analysis of ground test ops.(quantify saving of elimination of hydraulic valve)

NASA

ADVANCED DEVELOPMENT "BRIDGING PROGRAMS"
AGN&C

OBJECTIVE

To develop and demonstrate autonomous guidance, navigation and control technologies in areas of:

- New sensors and sensing devices
- Ground and onboard guidance algorithms
- Navigation and control algorithms
- Vehicle monitoring systems for autonomous ascent GN&C systems

PAYOFFS

Increased launch probability

Improved ascent/entry wind measurement technology

Improved abort planning and failure adaptability

Reduced cost from improved operations

NASA

AGN&C BRIDGING TEAM

JSC

- Lidar Operational Requirements Definition
- AGN&C Trade Studies

LaRC

- Solid State Lidar Demo and Technical Proposal

AGN&C Bridging Program

MSFC

- CO2 Lidar Demonstration and Technical Proposal

KSC

- Support of Lidar Demonstrations and Operations Planning

AGN&C FY91 LOW POWER LIDAR DEMONSTRATIONS

TEST PLAN

CONDUCT DAILY EXPERIMENTS TO ENABLE EXTRAPOLATION TO A FULL POWER SYSTEM CONSISTING OF CALIBRATION USING HARD TARGET AND BACKSCATTER PROFILES

CONDUCT EXPERIMENTS TO ESTABLISH RELATIVE PERFORMANCE DATA BASE:

- Jimisphere
- Rawindsonde
- Radar Wind Profiler
- Instrumented Shuttle Training Aircraft
- Tower Mounted Anenometer Network

NASA

Aluminum-Lithium
Bridging Activities

OBJECTIVES

Validate the readiness of Aluminum-Lithium(Al-Li) alloys for Space Transportation Needs

Demonstrate the viability of Al-Li alloys by a sublength, full diameter External Tank demo build

Identify processes and hardware required for the manufacture of an Al-Li cryotank.

PAYOFFS

Weight reductions allow robust designs and increases in safety and reliability

Design studies indicate 10-15% potential weight savings

NASA

AL-Li BRIDGING TEAM

MSFC

- Al-Li Alloy Characterization (ALCOA 2090 and Weldalite)
- Weld Processes/Techniques Definition
- Demo/Build/Test a sub-length full diameter external tank

LaRC

- Al-Li Alloy Characterization
  - –Superplastic forming
  - –Net shaped forming
- Automated Weld Process and NDE Processes for Fabrication

AL-Li Bridging Program

NASA

PROPOSED FY93 NEW BRIDGING TASKS

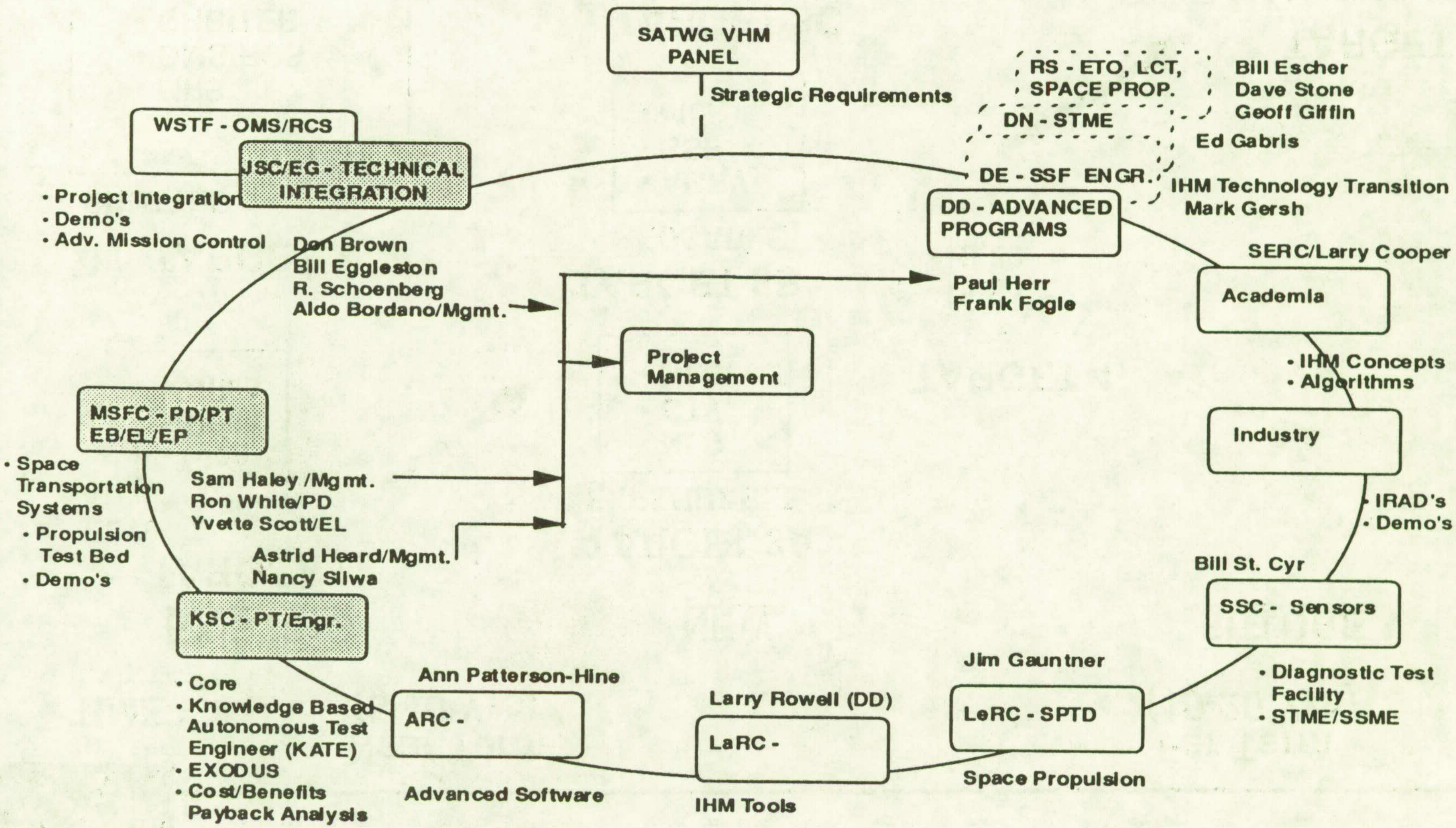
OSSD TECHNOLOGY ASSESSMENT ACTIVITIES HAVE RESULTED IN IDENTIFICATION OF POTENTIAL NEW BRIDGING TASKS IN:

- ***INTEGRATED VEHICLE HEALTH MANAGEMENT***
  - Engine/Propulsion Systems/ Components
  - TPS/Structural Element Measurements
  - Advanced Transducer/Sensor Demos
  - Other Subsystems (Power, GN&C, ECLSS)

IVHM BRIDGING PROGRAMS OBJECTIVE:

- **To Integrate And Demonstrate Practical Systems Level IVHM Concepts To Prove That Significant Operational Benefits And Cost Savings Will Be Gained By Implementation Of Future Launch Vehicles And Other Space Transportation Elements**

TEAM/ MANAGEMENT STRUCTURE



TARGET VEHICLE SET

TIME →

Near Term (5-10 Yrs) | **Far Term (10-20 Yrs)**

EXISTING

TARGET 1
ELVs
- Titan
- Delta
- Atlas

TARGET 2
SHUTTLE
- MPS
- OMS/RCS
- ORBITER SYSTEMS
- SRB
- OPS

NEW

TARGET 3A
EXPENDABLE
- NLS
- CTV
- HLLV

TARGET 3B
REUSABLE
- ACRV
- SSF
- etc.

TARGET 3C
SHUTTLE DERIVED
- MPS
- SRB
- CTV

TARGET 4
- PLS
- HL20

FUTURE

TARGET X
Lunar Lander
TLI
Mars Transfer
etc.

BENEFITS/DIRVERS

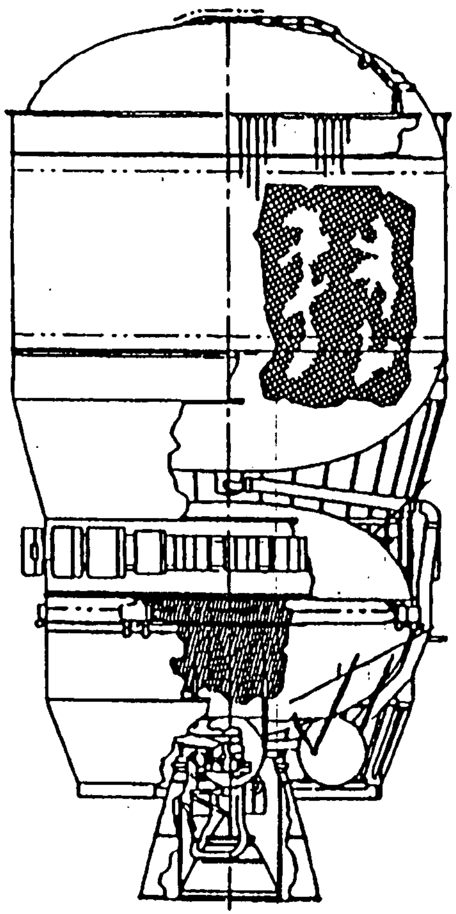
	COST	RELIABILITY	OPERABILITY
TOP PRIORITY			
Real time engine diagnostics		X	
Leak detection	X		
IVHM Architecture		X	
Ground processing Integration			X
IVHM for EMA			X
OMS/RCS	X		
IVHM Cost/Payback analysis*	X		
DESIRABLE			
Post flight/test data analysis for engines	X		
IVHM for mission operations	X		
Automated Inspection techniques for engines	X		
Flight/ground test plume spectroscopy			X
Laser pyros			X
SSF Fault Management system	X		
Hybrid Reliability/fault tolerance/cost tool	X		

* Application required for all demos

SELECTED DEMONSTRATIONS SUMMARY

	OBJECTIVE	FACILITY	BENEFIT
REAL TIME ENG. DIAG.	SENSOR & SW VALIDATION	MSFC SSME TTB & SSC TESTBEDS	SAFE SHUTDOWNS-TEST, HOLD-DOWNS, FLIGHT
LEAK DETECTION	AUTOMATIC MONITORING FOR LEAKING FLUIDS	MSFC MULTIPURPOSE H2 TESTBED & SSC	REDUCE GND. OPS COST, ENHANCE SAFETY
IVHM ARCHITECTURE	UTILIZE TEST BED TO VALIDATE AVIOINICS SUPPORT FUNCTIONS	JSC - JAEL	HIGH CONFIDENCE /SYST. LEVEL INTEGRATION
GROUND PROCESSING INTEGRATION	DEMO GND. PROCESSING FOR PLANNING/SCHED.	KSC ENGINEERING DEVELOPMENT LAB	REDUCE GND. OPS COSTS
IVHM FOR EMA	DEMO VHM FOR EMA SYST. INCLUDING PWR. & AV. INTERFACES	MSFC COMPONENENT LAB, CONTRACTOR LAB	REDUCE GND. OPS COST, ENHANCE SAFETY
OMS/RCS	DEVELOP NON-INTRUSIVE SENSORS/SOFTWARE FOR RCS PRESSURE REG. & VALVES.	OMS/RCS FLEET LEADER TEST ARTICLE - WSTF	REDUCE TURNAROUND, IMPROVE SAFETY, MINIMIZE FLUID LINE DISCONNECTS.

CURRENT BRIDGING PROGAMS SUPPORT CENTAUR EVOLUTION



Al-Li Alloy Structures
- 11% Lower weight than 2219 Al

EMA (ELA) TVC
- Enables automated end-to-end C/O
- Assembly & C/O Savings >1000 hours
- Improved reliability - Failure probability reduced by factor of 8
- 35 lb. Weight reduction
- Eliminate engine driven hydraulic pumps & system
- Eliminate ground hydraulic support equipment

EMA (ELA) Fluid Systems Valves
- Compatible with automated health monitoring & BIT
- 60% Reduction in C/O time with BIT
- Compatible with fault tolerant design

Automated Ground Health Management System (IVHM)
- 3 Day reduction in on-stand processing time
- Eliminates 30 stripchart recorders
- Modular infrastructure for growth/upgrades
- Efficient anomaly analysis and isolation
- Integrated control and display system
- Avoids break in inspection, setup, C/O, analysis and closeout when problems occur

Adaptive Guidance Navigation & Control (AGN&C)
- Automated mission planning with 6:1 reduction in planning time
- Reassignment of payloads in 5 days

NASA

ADVANCED DEVELOPMENT "BRIDGING PROGRAMS"

Summary

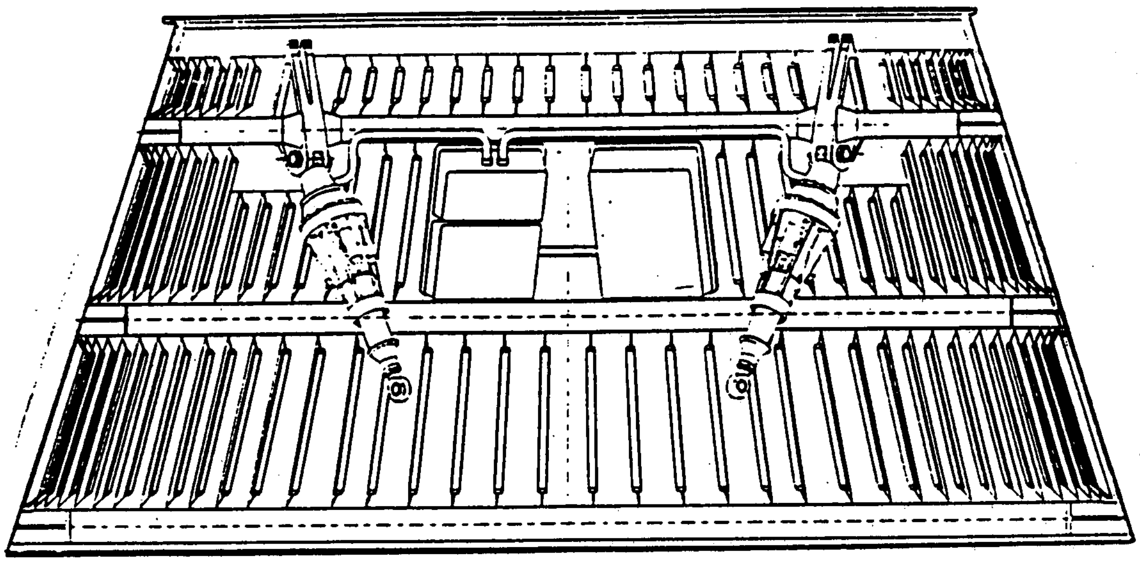
- "BRIDGING" THE GAP BETWEEN TECHNOLOGY DEVELOPERS AND USERS IS KEY TO SUCCESSFUL TECHNOLOGY TRANSFER/INSERTION
- CURRENT BRIDGING PROGRAMS ARE SERVING AS "PILOT PROJECTS" FOR TECHNOLOGY TRANSFER/INSERTION PROCESS WITHIN NASA
  - To date, technical progress is good
  - Demonstrating how well small intercenter groups work together
  - Stimulating significant interest with all NASA centers
  - Industry cooperation/cost sharing is gaining momentum
- BRIDGING PROGRAMS OFFER "NEW WAYS OF DOING BUSINESS"
  - Leverages technical excellence from NASA centers and industry
  - Places agency "gain sharing" ahead of "not invented here"
  - Focuses on needs of user
  - Recognizes budget and schedule constraints
- ATTENTIVE MANAGEMENT OF TECHNOLOGY BRIDGING IS VITAL FOR EFFECTIVE TECHNOLOGY TRANSFER

September 29, 1992

ELECTRIC ACTUATION

TECHNOLOGY BRIDGING PROJECT WORKSHOP

STS HYDRAULIC VS. ELA OPERATIONS SRB ASSESSMENT

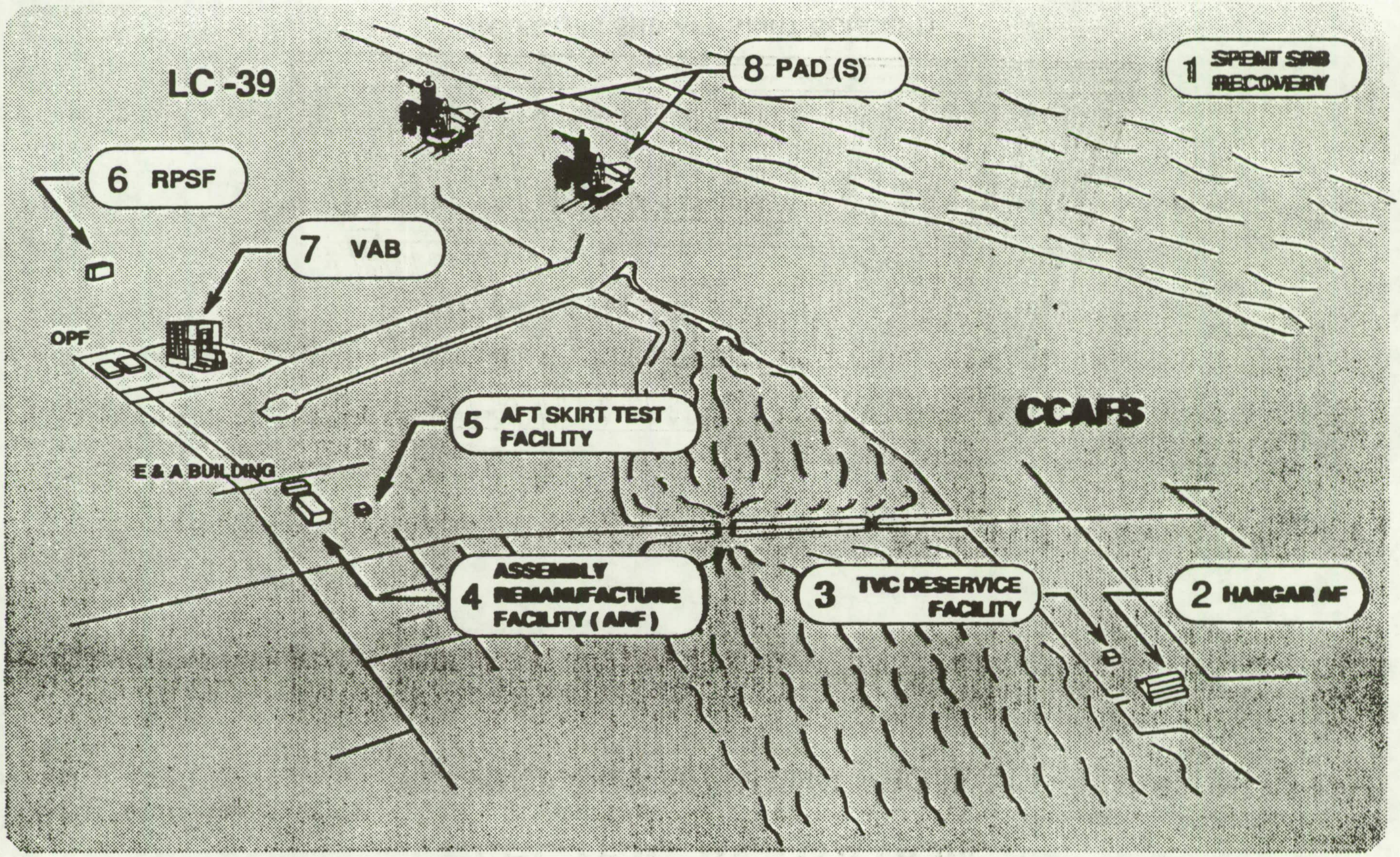


(ELECTRIC SRB AFT SKIRT CONCEPT)

Carey M. McCleskey, NASA/KSC
Haley W. Rushing, ASSI/KSC

LAUNCH SITE ELECTRIC ACTUATION STUDY

PRIMARY SRB TVC LAUNCH SITE WORK FLOW / SEQUENCE(S)



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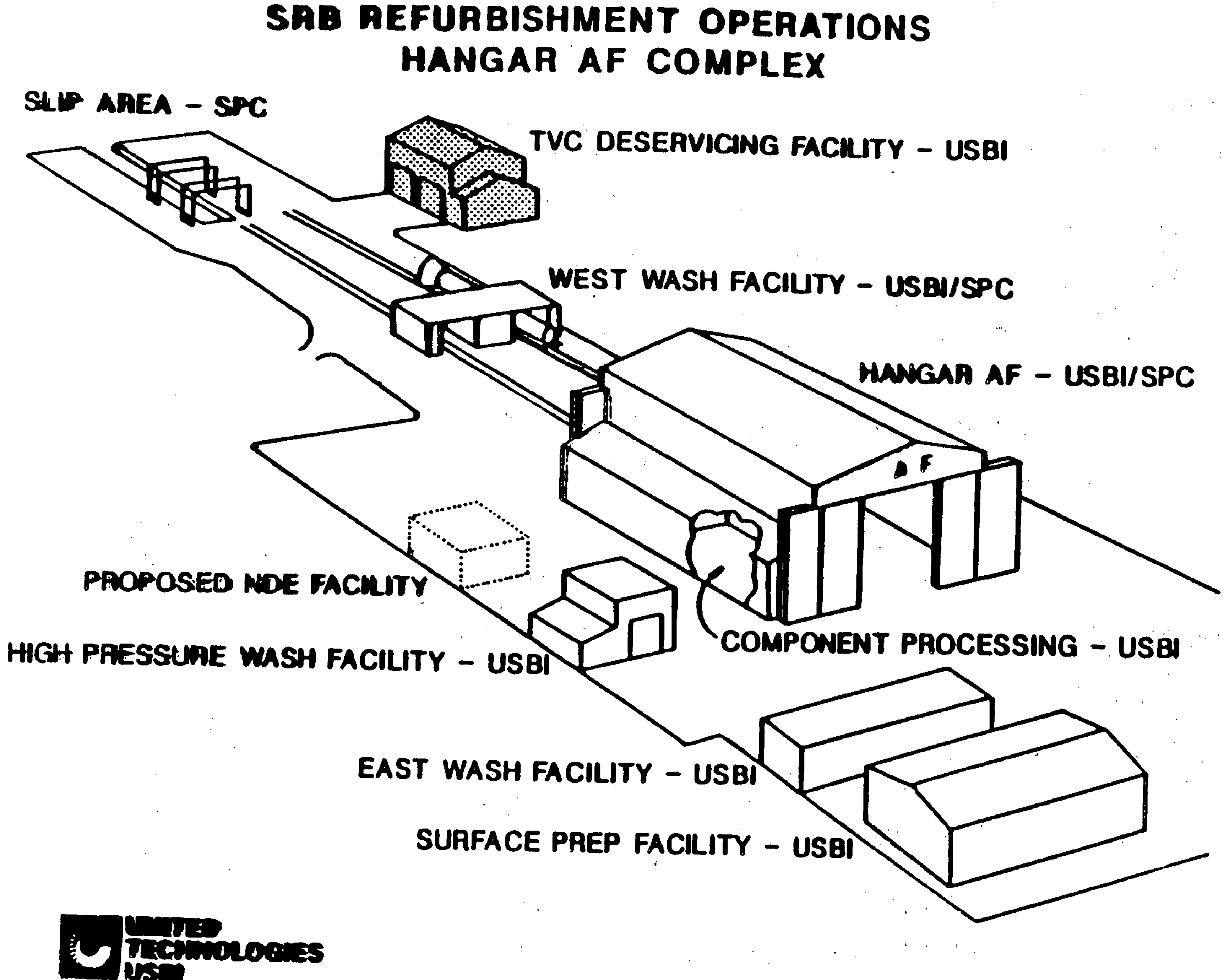
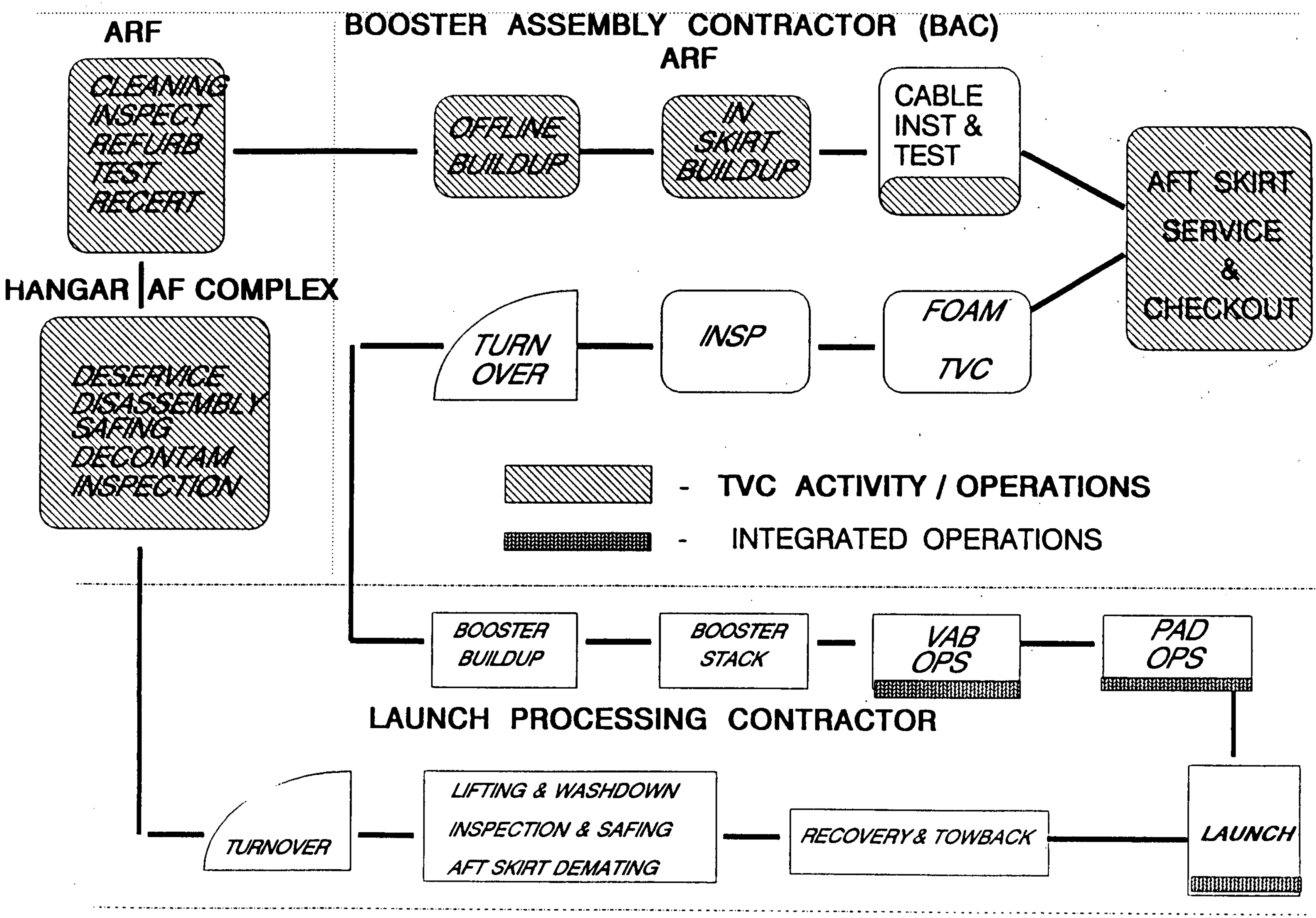


FIGURE 2.2.1.1-1

SRB TVC HARDWARE FLOW AND FUNCTIONS



ASSEMBLY AND REFURBISHMENT FACILITY (ARF)

MANUFACTURING BUILDING

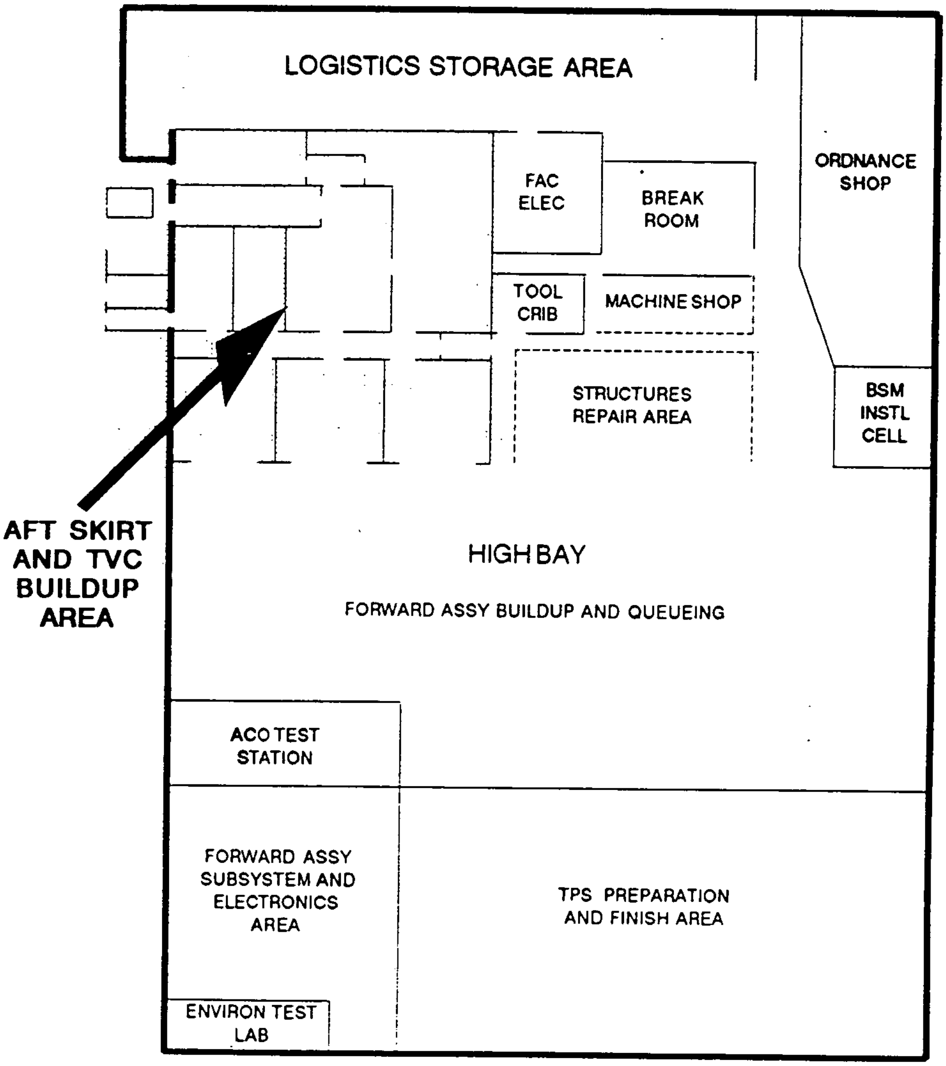
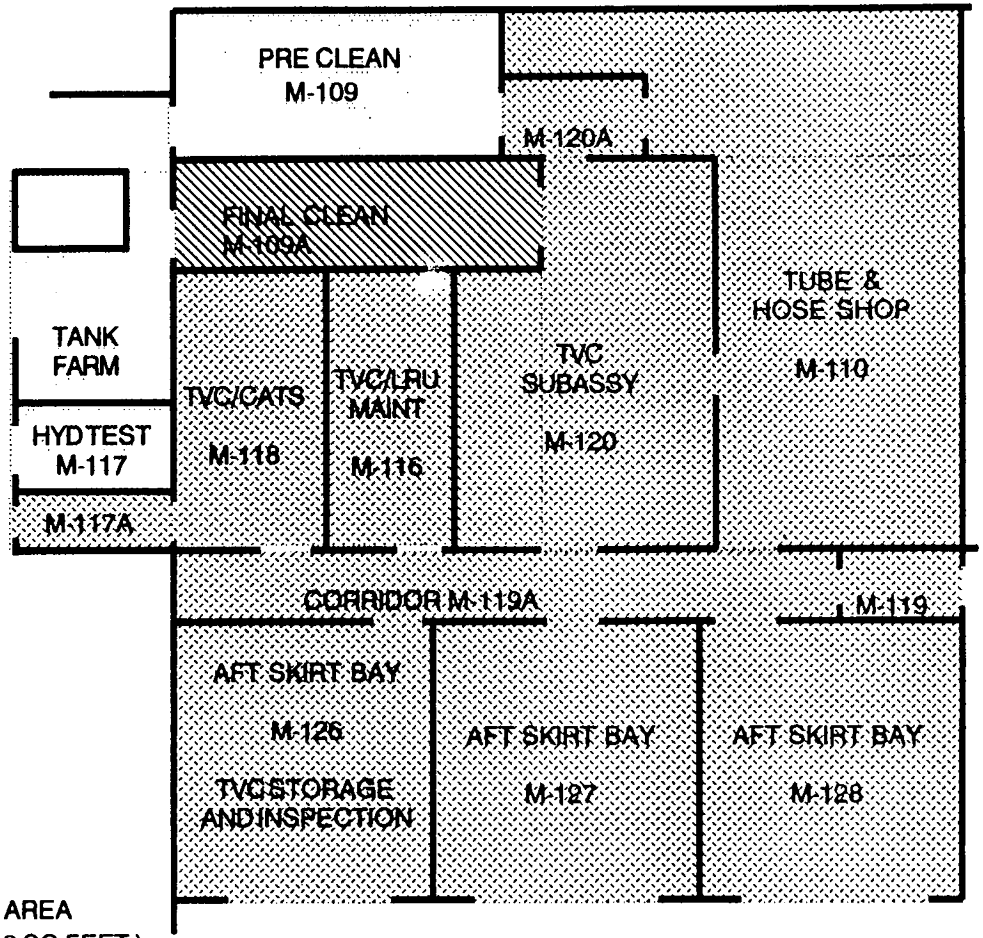


Fig 2.2.1.2.1-1

ARF MANUFACTURING BUILDING TVC AREAS

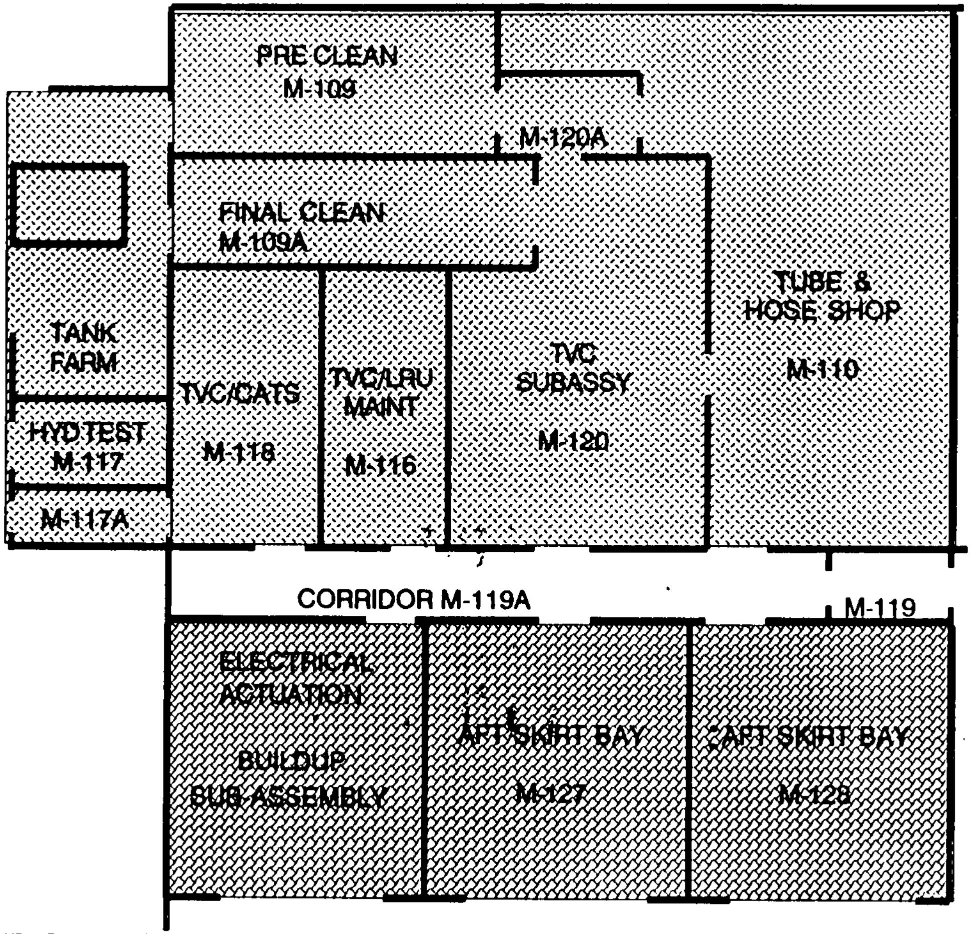


SYMBOLS

- 100 K AREA (10843 SQ FEET)
- NON CLEAN AREA (1089 SQ FEET)
- EXPLOSIVE PROOF & 100 K AREA

APU/HYDRAULICS TYPE TVC

ARF MANUFACTURING BUILDING TVC AREAS

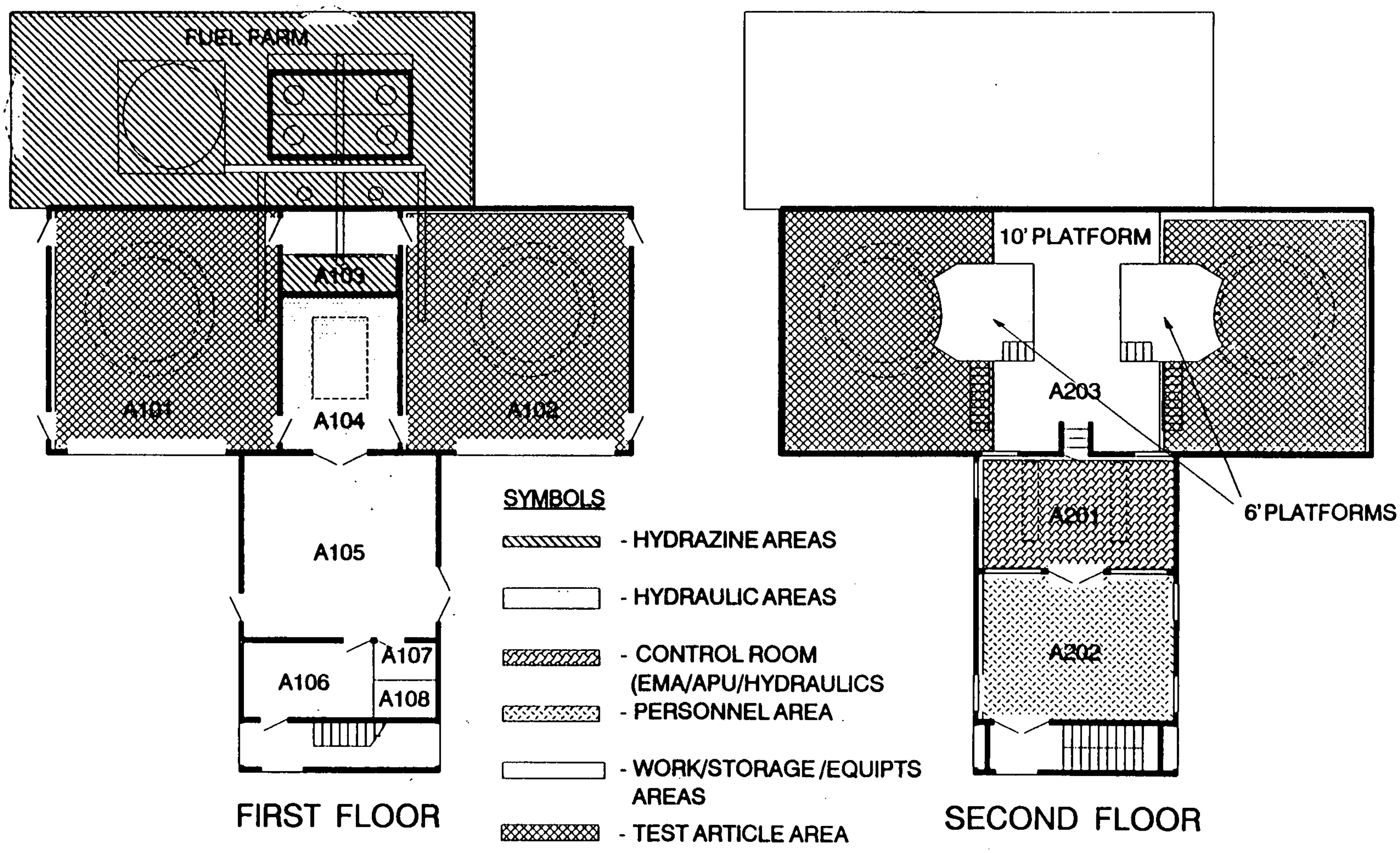


SYMBOLS:

- MANUFACTURING AREAS FOR APU / HYDRAULICS WHICH ARE NOT NEEDED FOR ELECTRICAL TVC SYSTEM

- MANUFACTURING AREAS FOR ELECTRICAL ACTUATION SYSTEM (3490 SQUARE FEET)

EMA
TYPE TVC



AFT SKIRT TEST FACILITY AREAS vs OPERATIONS

TVC MANUFACTURING APU/HYDRAULICS vs ELECTRICAL ACTUATION

OPERATION/FUNCTION	CURRENT SRB AREA ROOM	CURRENT SRB AREA SQ FT*	NEW PROJECT WITH APU/HYD REQ	NEW PROJECT WITH EMA REQ.
PRE CLEAN	M109	839*	YES	NO
FINAL CLEAN	M109A**	666	YES	NO
TANK FARM (OUTSIDE AREA SEE NOTE 1)	-	-	YES	NO
TUBE & HOSE FACILITY CLEAN RM ANTE ROOM AREA CORRIDOR	M110 M119A M119	2526 529 155	YES	NO
LRU MAINTENANCE SHOP (COMP ASSEMBLY)	M116	550	YES	NO
HYDRAULIC PUMP ROOMS (CATS TEST MEDIA)	M117	250*	YES	NO
HYDRAULIC & HYDRAZINE COMP ACCEPTANCE TEST CLEAN ROOM ANTE ROOM	M118 M117A	898 440	YES	NO
SUB ASSEMBLY AREA ANTE ROOM (PRE CLEAN TO HOSE SHOP)	M120 M120A	1431 158	YES	NO
AFT SKIRT TEST BAYS	M126*** M127	1174 1158 1158	YES	1174 1158 1158
TOTAL SQ FT 100K AREA NON CLEAN AREA TOTAL		10843 1089 11932	10843 1089 11932	 3490 3490

* NORMAL MAUNFACTURING AREA I.e. NOT 100K CLEAN

* EXPLOSION PROOF AREA

*** M126, ASSEMBLY CELL CURRENTLY USED AS INSP/WORK STATION

NOTE 1: OUTSIDE & WEST OF ROOMS 109 & 109A; TANKS FOR THE

DEIONIZED WATER	SUPPLY -3000 GALS	255 GALS WASTE
FREON	SUPPLY -225 GALS	225 GALS WASTE
ALCOLHOL	SUPPLY -3000 GALS	3000 GALS WASTE

SRB C I L LRU 's ASSESSMENT

SUMMARY

	APU/HYDRAULICS	ELA *
TOP 20	9	0 TO 1
CRIT 1 (INCLUDES ITEMS IN THE TOP 20)	194	1
CRIT 1 R	8	3
TOTAL TVC	202	4 TO 5
TVC + TVC ELECT SUPPORT LRUS	205	8 TO 9**
TVC % OF SRB CIL LRU's	34 %	2 % of reduced SRB CIL's with deletion of APU/HYD TVC

* ASSUMES NO LRU's EXPLOSIVE OR WHICH PROPAGATE FIRE

** INCLUDES CAT 1 ATVC INTERFACE BOX, + 2 CAT 1R CABLE HARNESS, + 1 CAT 1R POWER HARNESS

SRB TVC AFT SKIRT ASSEMBLY AND REFURBISHMENT*

APU/HYDRAULICS vs ELECTROMECHANICAL ACTUATION

OPERATION	ONE FLIGHT VEHICLE OR 2 AFT SKIRTS APU/HYDRAULIC WORK DAYS	 ELA WORK DAYS
DESERVICING	5	NOT APPLICABLE
DISASSEMBLY FROM AFT SKIRT AND MODULE	15	2
OFFLINE BUILDUP	38	4
IN SKIRT BUILDUP	32	10
AFT SKIRT SERVICE & CHECKOUT (NOTE FOR ELA NO SERVICING REQUIRED)	10	4
TOTAL	100	20

* LRU/COMPONENTS INSPECTION REFURBISHMENT, TEST AND CHECKOUT IS COVERED AS A COST ITEM.

SRB TVC
APU/HYDRAULICS VS. ELECTROMECHANICAL ACTUATION LRU/COMPONENTS INSPECTION REFURBISHMENT, TEST AND CHEKCOUT COSTS

APU/HYDRAULICS		ELECTRIC ACUTATION	
LRU/COMPONENT	MISSION SET AVERAGE COST	LRU/COMPONENT	MISSION SET ESTIMATED COST
O Off-Site Vendor			
O Hyd. Power Unit			
O APU	590,000	O Electric Power Battery/each mission	$ 80/160 K*
O Hyd. Pump	22,000		
O Actuators	323,600	O Actuator Assembly	63/125 K
		O Controller**	2.2 K
O On-Site Contract (TBE)(Reservoirs, Accumulators, Mani-fests, check valves,filters, etc.)	216,328		
	$1,151,928	ELA	$149,000 to $287,000

* Depends on Battery Type Selected

** Assumed protected from salt water contact and requires on-site bench test and inspection only.

INTEGRATED OPERATIONS

APU/HYUDRAULICS VS. EMA

OPERATION		APU/HYD SERIAL HOURS	EMA SERIAL HOURS
RECOVERY/SAFING		4	0
SIT (PART 1) VAB		27	6.5 (1 Shift)
SIT (PART 2) PAD		42	14.5 (2 Shifts)
TVC FUELING PAD		42	0
	TOTAL	115 eh	20.5 (3 shifts)

STUDY ASSUMPTIONS FOR THE SRB ELECTRICAL ACTUATION THRUST VECTOR CONTROL (TVC)

O There are no launch site operations differences between the ELA schemes being considered.

  o Induction motor with resonant controller
  o Permanent magnet brushless DC motor and controller

O The controllers will incorporate a Health Management System

O Manufacturing and electrical shop environment are adequate for ELA (clean bench for LRU internal disassembly for modifications or repair only)

O Items cost economical to refurbish will be recovered and reused (all major functional LRUs). (The LRUs are protected from internal salt water intrusion.)

O Expendable items are cables and ancillary hardware (fasteners, bonding straps, clamps) which have salt water contact.

O Fueling, servicing, bleeding, pressurizing, and deservicing operations with the associated fluids and gases sampling, certification, and air entrainment checks are not required.

STUDY ASSUMPTIONS FOR THE SRB ELECTRICAL ACTUATION THRUST VECTOR CONTROL (TVC) (Continued)

- O TVC "Scape Suit" hazardous operations with associated area clears, and health and fire department support, are eliminated.

- O Protection against high voltage DC contact by personnel for launch operations will be provided in the design.

- O POWER SOURCE

  - o Chemical batteries (long term) are expendable; require no activation; and can be stored in an ambient environment. Battery life after installation shall nominally be one year with a minimum of 120 days. Short term and interim chemical batteries (primary, reserve, or high temp) will provide a pad stay time which supports 24, 48, and 72 hours' scrub turn-around. Primary and reserve batteries shall accommodate two (2) low-rate trickle charge without requiring removal, throwing away, and replacement in the event of contingency rollback.

  - o Flywheel battery controller will include a health management system; be capable of being charge up from ground umbilical source; meet 24, 48 and 72 hours' scrub turnaround requirement without spin up (recharge); provide self containment protection against credible failure modes.

EMA CONTROL SYSTEMS DESIGN OPERATIONS PROVISIONS

- LRUs will be readily accessible for Installation and Removal. The movement of control surfaces and engine nozzles for access shall not be required. Connectors shall be visible and within "easy" reach from personnel support structures.

- External pods providing for TVC system (controllers, power source, cables, and ancillary hardware) protection from salt water contact and for external removal and reinstallation are to be considered. This would facilitate the recovery and reuse of multi-mission hardware and alleviate requirements for complete disassembly and rebuild.

- Operations and maintenance requirements at the LRU and system level, including failure detection and isolation, will be implemented in the HMS and Bite (automated test) with no requirement for external stimuli. This will include redundancy tests. The procedures and software implementing these requirements shall be modular; capable of stand-alone application; provide for new version or technology enhancement; and verified at the post-manufacturing/assembly level. Thermal profiles of the LRUs shall be developed and checked during LRU acceptance test and used for failure prediction/health status.

- The HMS system, OMRS system, and Launch Processing systems shall be "TRULY" operations "USER FRIENDLY" with automatic display of the critical TVC operations and parameters necessary for launch testing. The HMS system, failure prediction, failure trend, and LRU component history (waivers/deviations, open work, approved changes) data busses will provide for access, running of sequences, and display of data to the TVC LPS console for contingency, troubleshooting, and engineering evaluation.

- Factory environment (temperature and cleanliness) shall be adequate for normal LRU processing. Contingency internal LRU operations shall, if required, be performed using "Clean Bench."

- Fasteners with locking and self capture features are to used for LRUs' installation and on access covers respectively.

- Bonding straps, when required, will be provided with the LRU and nominally installed during Post-Manufacturing, Checkout/ACO PMC buildup and test.

- LRUs will be internally protected against electrostatic charge during mate/demate of connectors with no requirements for protective clothing and grounding of personnel.

EMA THRUST VECTOR CONTROL (TVC) SYSTEM
LAUNCH SITE VERIFICATION REQ (GENERIC)

REQUIREMENT	Actuator Assembly	Controller Assembly	Power Supply	TVC Subsystem	Remarks
Isolation				X	Isolation at LRU level performed at post-manufacturing checkout/assembly checkout
Power-Up Sequence	X	X	X	X	Verifies TVC subsystem operation and compatibility with Launch Area GSE power source and Launch Processing System (LPS).
Verify LRU Health and Status	X	X	X	X	Automatic GO-NO GO test with Launch Processing System asking the on-board TVC HMS to perform status check including redundancy. NOTE: On-board and ground processing S/W previously run at post-manufacturing/ACO°
Control System Verification				X	Vehicle guidance and control system previously verified at PMC before delivery for launch operations processing. Launch operations GN&C system health and status checks performed. Test verifies command and proper response of TVC system interfaced to vehicle system, including normal operations and redundancy checks. Test is to be run with actuators unconnected to nozzle. Envelope/clearance tests, if required, have been performed during PMC. Contingency test or re-test at LRU level to be within capability of the control health management system.
Countdown Demonstration				X	Performed as separate test on first flow, after major modification affecting launch sequence, etc. Verifies control system network compatibility, system operation, and launch countdown.
FRF				X	Not required by EM TVC; verifies TVC control in conjunction with engine firing when required for MPS engine changeout, MPS modification, etc. verification.
Launch				X*	Verifies TVC system end-to-end performance and readiness for launch while running through the automated power-up, bite checks, HMS self tests, flight critical measurements, and command system test profile. The command system test profile is to be run as soon as practical after transition to internal power.

* TVC system configured for launch and closeout.

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ELECTRICAL ACTUATION TECHNOLOGY BRIDGING PROGRAM

GALE R. SUNDBERG
NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135

ELA-TECHNOLOGY BRIDGING PROJECT WORKSHOP
MARSHALL SPACE FLIGHT CENTER, ALABAMA

SEPTEMBER 29, 1992

GRS92-005.1

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ELA TECHNOLOGY BRIDGING PROJECT WORKSHOP

- GOVERNMENT/INDUSTRY/ACADEMIA ELECTRICAL ACTUATION/ POWER SYSTEMS TECHNICAL INTERCHANGE MEETING
- NASA ELA TECHNOLOGY BRIDGING PROJECT REVIEW
- SEVERAL DEMONSTRATIONS OF ELECTRICAL ACTUATION SYSTEM TECHNOLOGIES
- PROVIDE A FORUM FOR NASA TO SHARE/DISCUSS ELA/POWER GOALS, PROGRESS, ISSUES AND PLANS
- OPEN WINDOWS OF OPPORTUNITY FOR TECHNOLOGY ACCEPTANCE AND TRANSFER

GRS92-013.12

Technology "Bridging" Concept

- "Technology Bridging" is a process that was spawned by the Strategic Avionics Technology Working Group (SATWG).

- It is a technology development and demonstration process that "bridges" technology providers and users.

- It is a joint endeavor between government, industry and academia.
- It employs principles of concurrent engineering.
- It produces credible costs-to-benefits assessment.
- It's objective is to facilitate technology transition, from the lab to the customer's project.

- Once the technology is incorporated into a program's advanced development phase, the bridging project focuses on other applications of the technology, or terminates, allowing resources to be transferred to other technology initiatives.

Electrical Actuation Technology Bridging Project Objectives

- Leverage NLS & industry IRAD ELA technology development to meet multiple NASA program actuation system requirements
- Develop and demonstrate a representative advanced technology, high-power (40-70 Hp) electrical actuation system suited for primary flight control (thrust vector & aerosurface control) applications. Customer/Program targets include: NLS, ASRM, CELVs
- Develop and demonstrate low-energy, high-reliability ELA systems suited for flight/ground fluid control (Propellant Control Valve, GSE) and future space transfer vehicle and remote surface vehicle (SEI) applications. Customer/Program targets include: KSC/SSC-GSE, NLS/ELV PCVs, ACRV F/C, and SEI (Rovers, Excavators, Cranes, OMV, OTV, Lander)
- Develop metrics to assess/validate cost benefits of electrical vs. conventional hydraulic actuation systems (flight and ground)
- Define and implement a cooperative, customer-focused technology development and transition process as a "pilot" for the agency
- Successfully transition proven ELA system technology into first available target program(s)

Electrical Actaution Technology Need

- PAYOFFS
  - Eliminate maintenance-intensive, high-pressure hydraulic systems
  - Eliminate centralized hydraulics and hazardous/toxic fluids
  - Reduce labor-intensive testing and vehicle preparation time (support rapid change-out & retest)
  - Reduce recurring launch processing & ops costs (~10% labor & GSE)
  - Improve program reliability, operability and abort recovery
  - Improve late hold capability and extend launch window
  - Reduce stand-down and vehicle turn-around times
  - Multiple national technology spin-off applications
    - -- electric auto
    - -- motorized machinery/appliances
    - -- more-electric airplane

NATIONAL LAUNCH SYSTEM

EMA'S APPLICABLE TO NATIONAL SET OF LAUNCH VEHICLES

	20 Hp EMA FOR COMMERCIAL ELV				40 Hp EMA		60 Hp EMA SYSTEM		
					STS FLT CONT.				
REQUIREMENTS	CENTAUR	ENGINE PRE-VALVE	TITAN III STAGE 1*	ATLAS BOOSTER	OUT ELE	IN ELE	ALS PREL.	STS TVC	SRB
STALL LOAD (LBS)	1610	X	29,790	10,750	54 K	65 K	48,000	74,400	96,840
DYNAMIC LOAD (at actuation rate) (LBS)	1191	X	11,330	7,510	39 K	48 K	32,000	48,000	
ACTUATION RATE (DEG/SEC)	6	X	10	9	30	30	15	10	10
ACTUATION POWER (HP)	0.5	2.1	4.3	6	13.7	28.5	32.8	41.6	68

* ('Applicable TVC for ALS and MOOG Position Statement', MOOG, INC., Missile System Div., East Aurora, NY 14052)

X - PARAMETER NOT APPLICABLE/AVAILABLE

NATIONAL LAUNCH SYSTEM

ELECTRICAL ACTUATOR COMPONENT HARDWARE TRADES

INVERTER/CONTROLLER UNIT

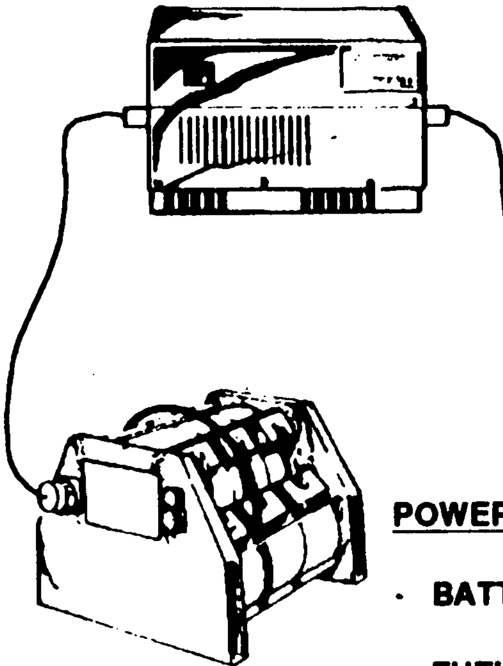
- HIGH FREQUENCY AC LINK: PULSE POPULATION DENSITY
- HIGH VOLTAGE DC LINK: PULSE WIDTH MODULATION

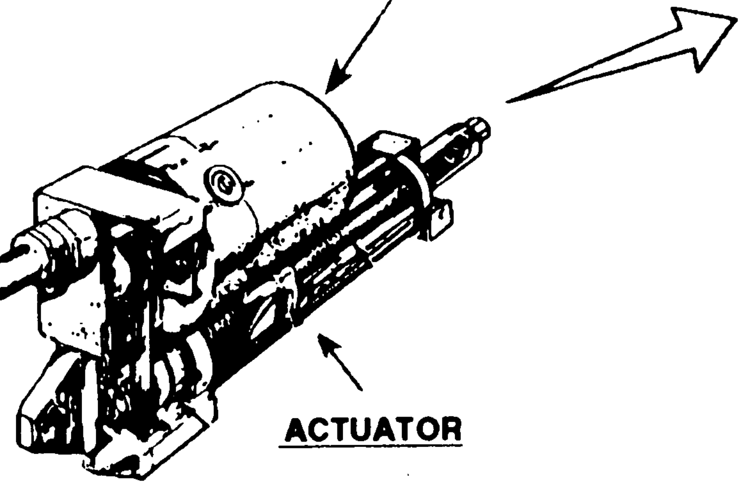
POWER/SIGNAL CABLES

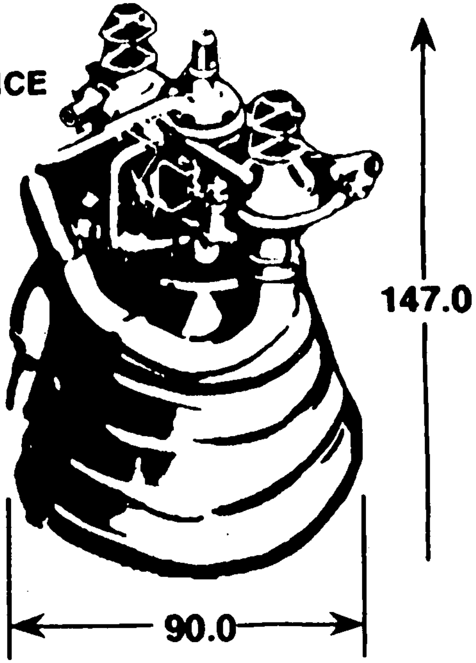
- LOW INDUCTANCE
- LOW EMI/EMC

ELECTRIC MOTOR

- INDUCTION
- SWITCHED RELUCTANCE
- PERMANENT MAGNET







ACTUATOR

- BALL SCREW
- ROLLER SCREW
- ELECTROHYDROSTATIC

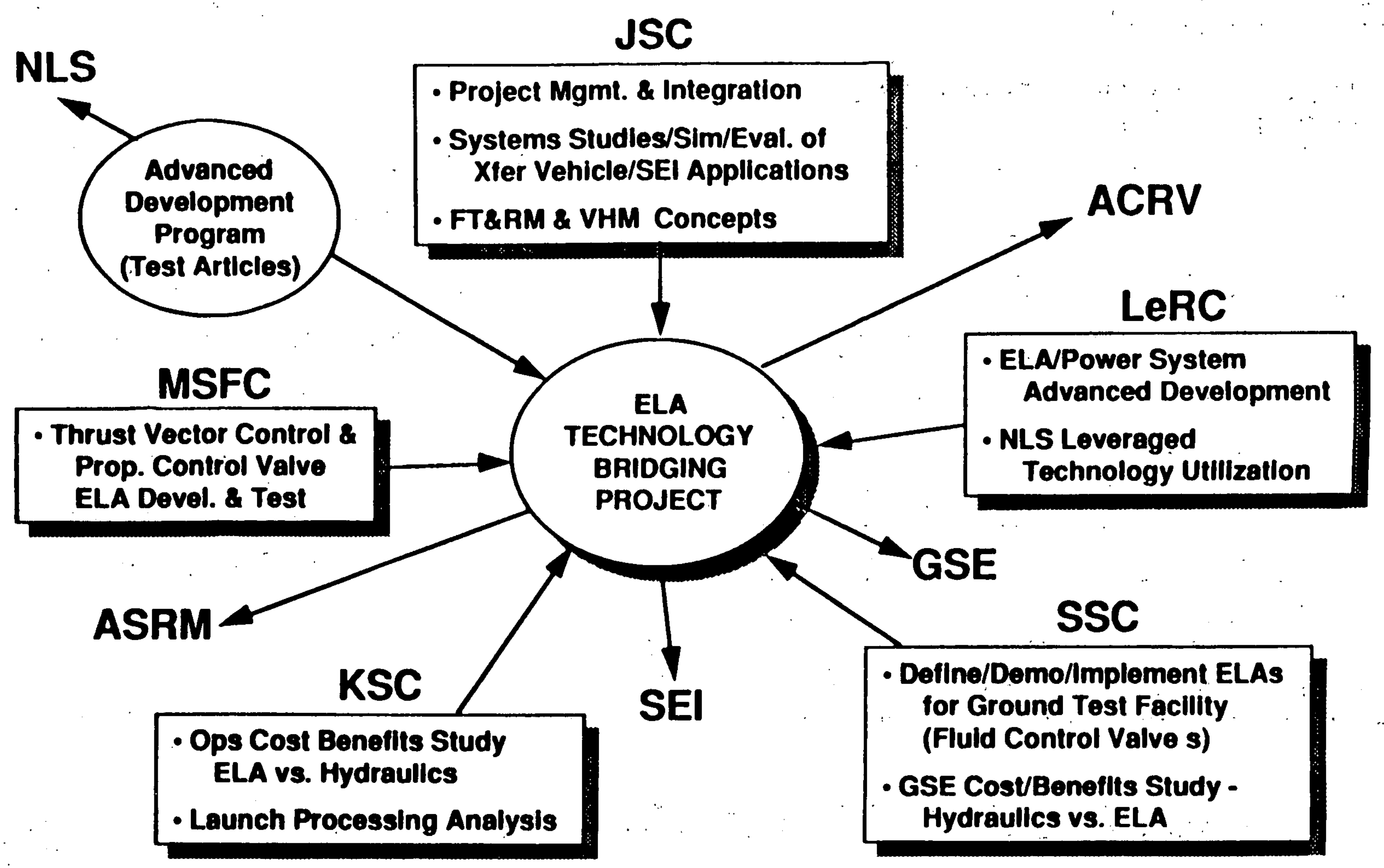
POWER SOURCE

- BATTERY
- FUEL CELL
- TURBO ALTERNATOR

STME/SSME AND FLIGHT CONTROLS

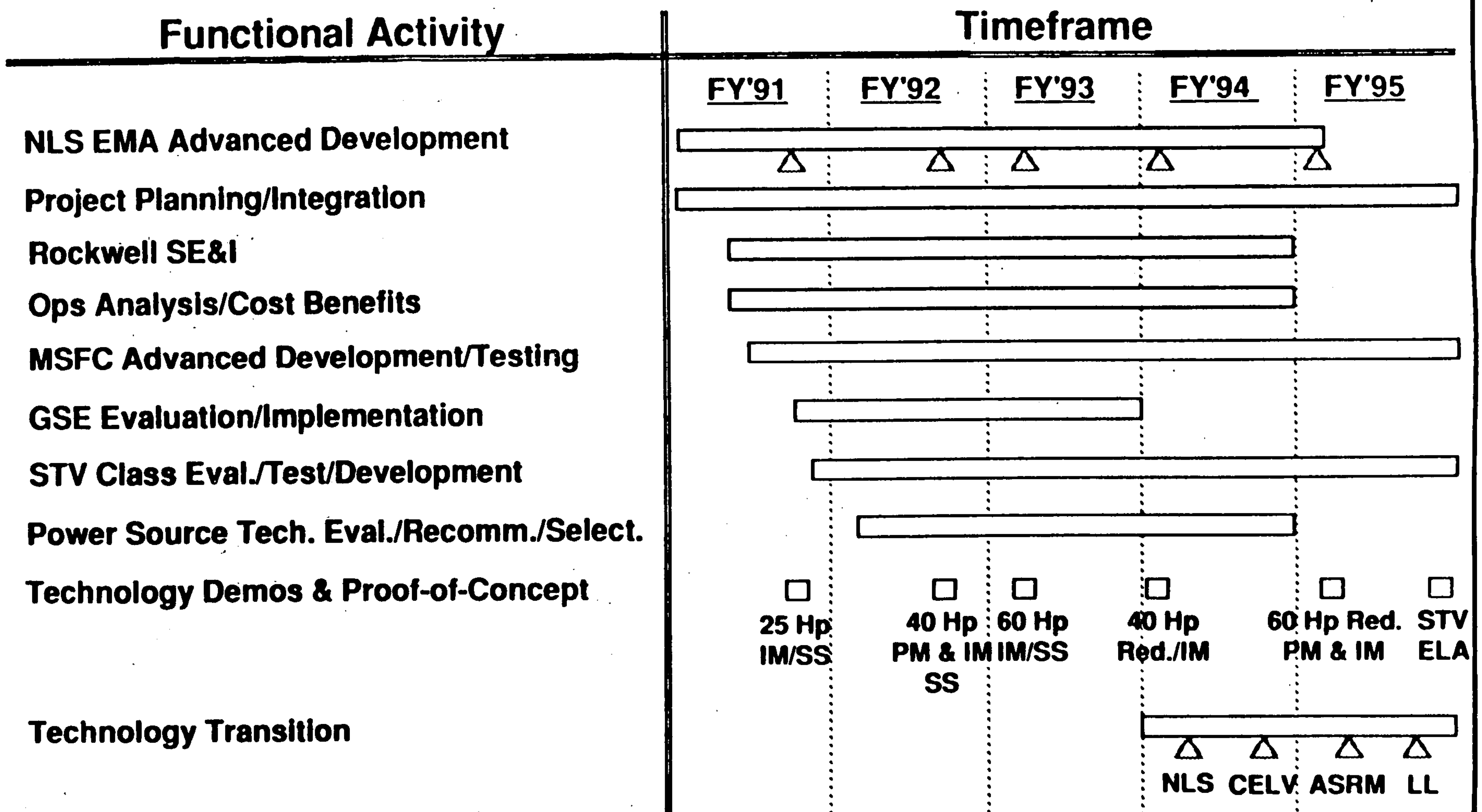
GRS92-006.10

ELA Technology Bridging Team/Roles



MWB6/1/92

ELA Technology Bridging Project Top-Level Schedule



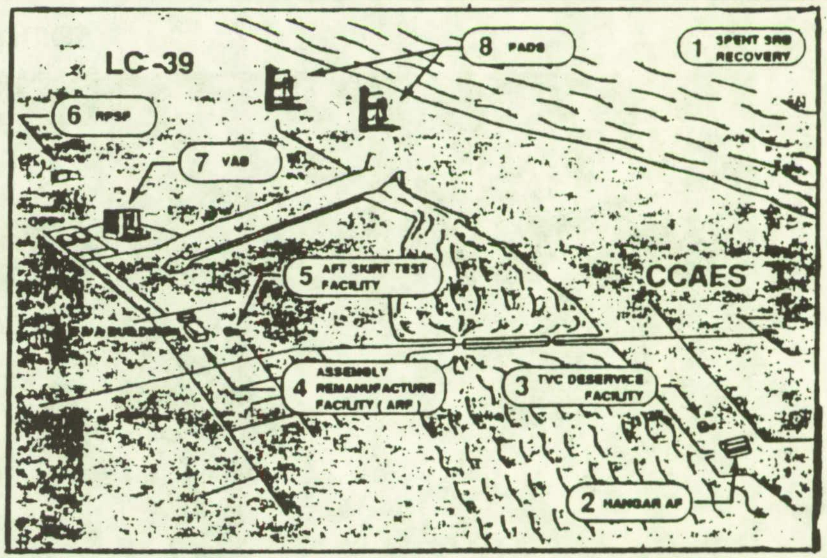
MWB6/1/92

SRB HYDRAULIC VS ELECTRIC LIFE CYCLE COST OVERVIEW

INTRODUCTION

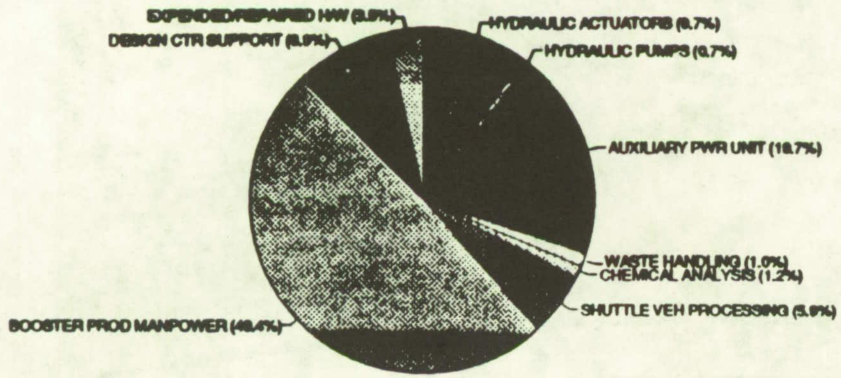
- SRB TVC LAUNCH SITE PROCESS
- LIFE CYCLE COST ANALYSIS INTERIM RESULTS
- LAUNCH SITE OPERATIONS REDUCTIONS
  - HUMAN RESOURCES (MAN-HRS)
  - EQUIPMENT
  - FACILITY
- BATTERY ISSUES

SRB TVC WORK FLOW /SEQUENCE



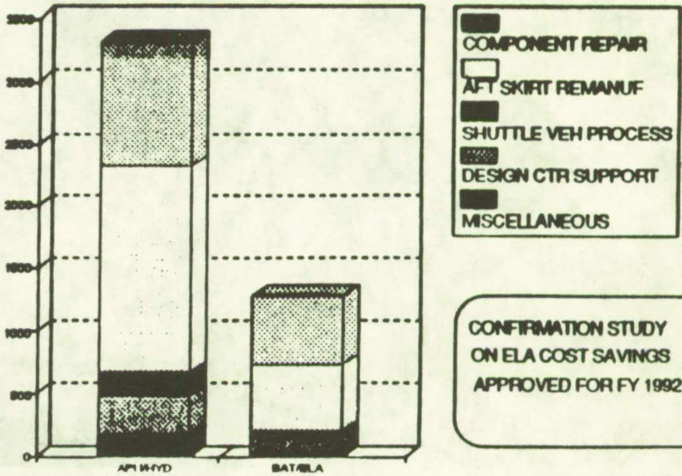
SRB TVC LIFE CYCLE COST ELEMENTS

(System Costs = $ 3.3M Per Flight)

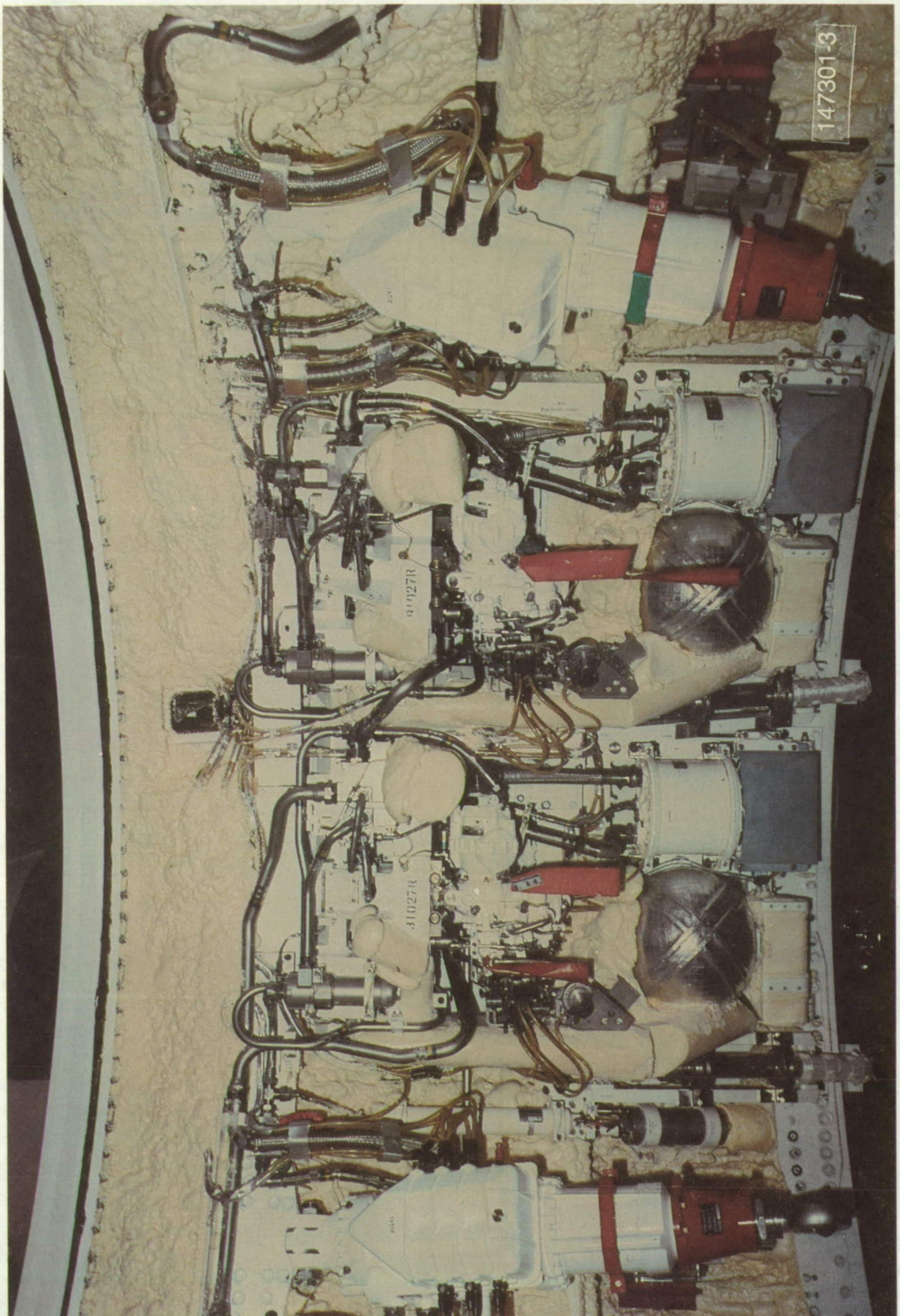


SRB TVC HYD VS ELA (INTERIM RESULTS)

(Cost Savings = $ 2.0M Per Flight)



CONFIRMATION STUDY
ON ELA COST SAVINGS
APPROVED FOR FY 1992



SRB TVC HYDRAULICS

LAUNCH SITE OPERATIONS REDUCTIONS

PROCESSING TIME REDUCTIONS (DAYS)

PROCESS ACTIVITY	APU/HYD	ELA
RECOVERY/SAFING	0.5	0
DESERVICE/DISASS'Y	6	1
COMPONENT DISASS'Y	15	4
AFT SKIRT REMANUF		
OFF-LINE ACTIONS	38	8
IN-SKIRT BUILD-UP	32	6
SERVICE, TEST & C/O	10	4
LAUNCH VEHICLE INTEG	1	0.5
PAD OPERATIONS	3.5	1
TOTAL	106	24.5

77% REDUCTION

HAZARDOUS OPERATIONS

HYDRAZINE HAZARD

SCAPE SUITS/TECHNICIANS

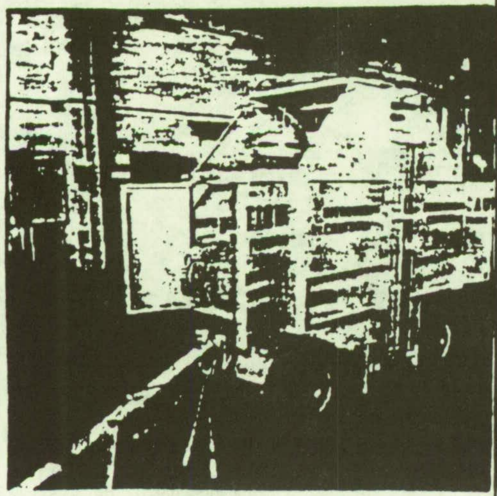
BREATHING AIR SERVICES

FIRE/MEDICAL SUPPORT

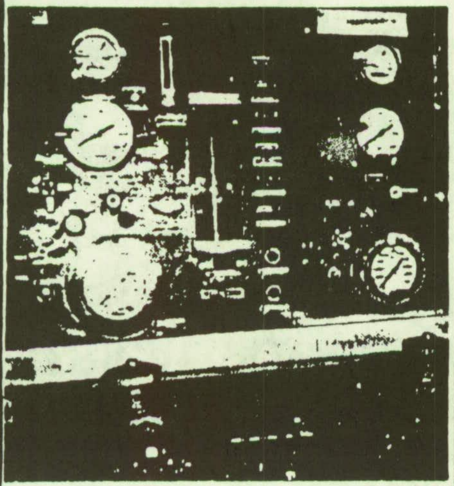
STORAGE & HANDLING

GROUND SUPPORT EQUIPMENT

APU



HYD



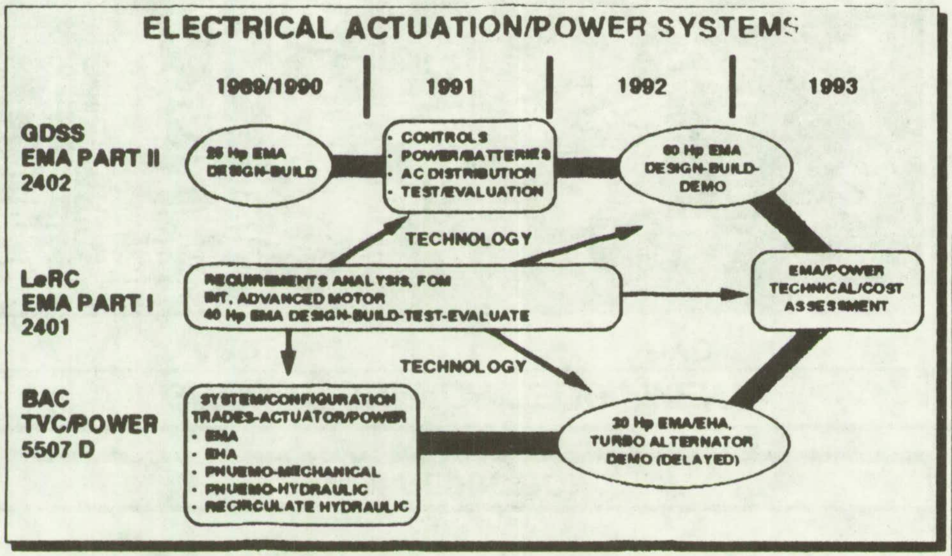
FURTHER BENEFITS

- GSE COUNT CURRENTLY AT <u>588 ITEMS</u> - ELA FAR LESS
- LESS UNSCHEDULED MAINT/PROBLEMS THROUGH LARGE REDUCTIONS IN VEHICLE COMPONENT & GSE COUNTS
- LARGE REDUCTION IN FLUID COMMODITIES HANDLING AND SERVICES:
  - HYDRAULIC FLUID
  - HYDRAZINE
  - ALCOHOL, FREON, HP GN2, BREATHING AIR, CLEANING AGENTS, DETERGENTS, ETC.
- FACILITY AREA FROM 12,000 TO 3500 SQ. FT. WITH NO REQUIREMENT FOR TWO OF THE FACILITIES

NATIONAL LAUNCH SYSTEM

AVIONICS

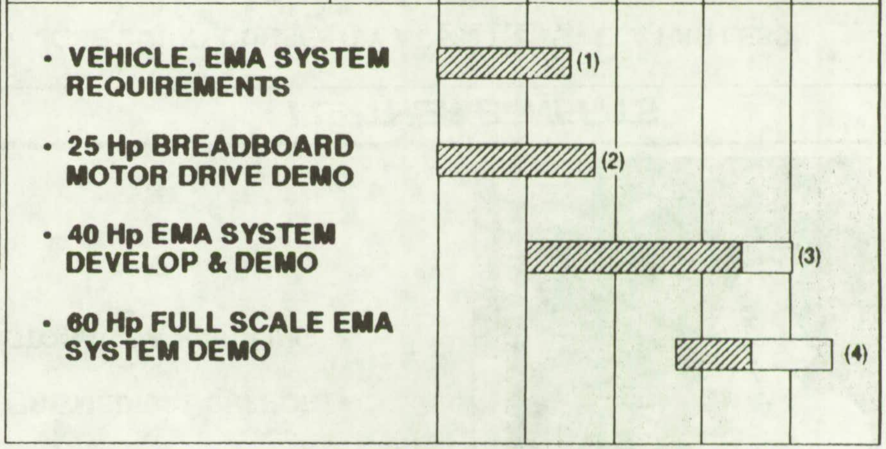
ELECTROMECHANICAL ACTUATORS & INTEGRATED ELECTRICAL POWER SYSTEM - PART I #2401



RESPONSIBLE ORG.: JPO, NASA/LeRC

EXECUTED BY: NASA/LERC, GDSS, BAC

FUNDING	1.25	1.54	2.53	1.03	0.86	0.69
FY	PRIOR	89	90	91	92	93



OBJECTIVE:

- DEMONSTRATE EMA/POWER SUBSYSTEMS FOR TVC AND ENGINE EFFECTORS
- INTEGRATE CONTROLS WITH AVIONICS AND PROPULSION INTERFACES

PAY-OFFS:

- ELIMINATION OF HYDRAULICS AND ASSOCIATED EQUIPMENT/FLUIDS
- REDUCE CHECK-OUT FLOWS/OPS. COSTS
- REDUCE STAND DOWN TIME/COSTS
- IMPROVE DISPATCH RELIABILITY, LAUNCH ON DEMAND

PRODUCTS/DELIVERABLES:

(1) VEHICLE TVC REQUIREMENTS & EMA/POWER SYSTEM REQUIREMENTS

(2) 25 Hp INVERTER/CONTROLLER BREADBOARD H/W DEMO (HIGH POWER, 20 kHz RESONANT LINK, FIELD-ORIENTED CONTROL OF MOTOR)

(3) 40 Hp EMA SUBSYSTEM DEVELOPED AND DEMONSTRATED (MOTOR CONTROLLER, ADVANCED INDUCTION MOTOR AND ACTUATOR)

(4) 60 Hp FULL SCALE EMA TVC SUBSYSTEM DEMONSTRATED (POWER SOURCE, CONTROLLER, MOTOR, ACTUATOR IN AVIONICS SYSTEM)

GRS92-007.1

NATIONAL LAUNCH SYSTEM

ELECTRICAL ACTUATORS FOR EARTH-TO-ORBIT

BASED UPON NLS ADP DEVELOPMENT

- **BATTERIES**
  - BIPOLAR LITHIUM; MASS = 2 kW/Lb.
- **POWER PROCESSING - RESONANT LINK**
  - FREQUENCY = 40 to 60 kHz
  - MASS = 0.5 to 1.5 Lb./Hp
- **INDUCTION MOTOR**
  - STEADY-STATE FREQUENCY = AS REQUIRED
  - FREQUENCY AT PEAK HORSEPOWER = 750 Hz (approx.)
  - MASS = 0.25 Lb. PER PEAK Hp
- **SYSTEM MASSES (AT 60 Hp PEAK FOR NLS)**
  - TOTAL SINGLE ENGINE - TWO ACTUATOR SYSTEMS = 520 Lbs.
  - COMPARABLE, MODERN DISTRIBUTED HYDRAULICS = 850 Lbs.

GRS92-008.12

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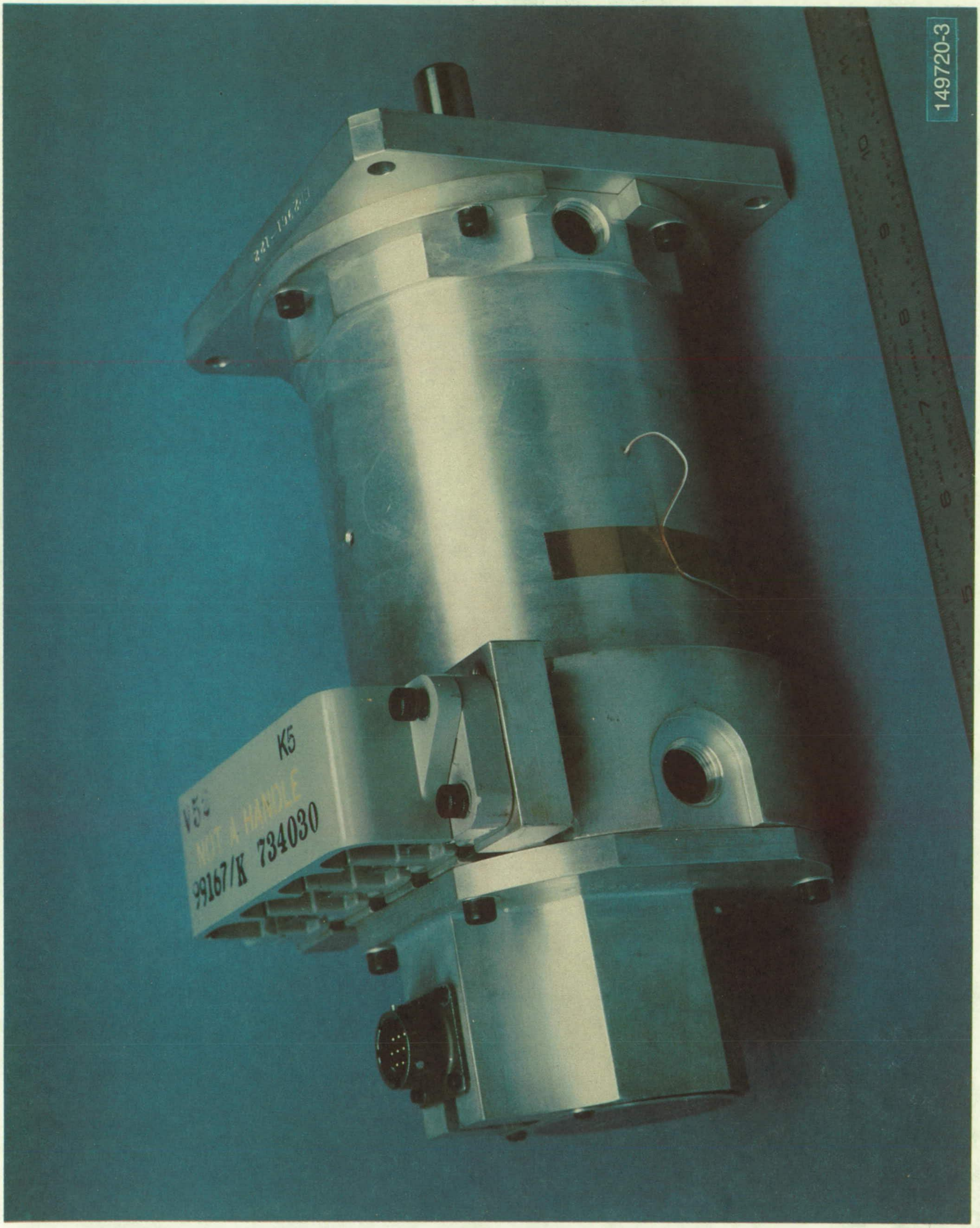
FULL SCALE, 60 HP NLS DEMONSTRATION SYSTEM

- MOTOR CONTROLLER
  - DEDICATED DC-LINK, RESONANT POWER PROCESSOR
  - 60 kHz, 75 KVA
  - SHARED MICRO-COMPUTER CONTROL, FIBER-OPTIC INTERFACES TO PROCESSOR AND MOTOR
  - PRIMARY CONTROL ALGORITHMS CONTAINED IN SOFTWARE
- MOTOR
  - ADVANCED, LIGHTWEIGHT (<20 LBS) THREE-PHASE INDUCTION MOTOR
  - 38 Hp CONTINUOUS, 70 Hp PEAK AT 14,700 RPM
  - LOW LOSS, LOW INERTIA ROTOR
  - HIGH TEMPERATURE OPERATION TO 200 C
- LINEAR ACTUATOR
  - BALL SCREW WITH DUAL MOTOR DRIVE
  - 48,200 LB FORCE, 5.4 INCH EXTENSION
  - WEIGHT IS ABOUT 225 LBS



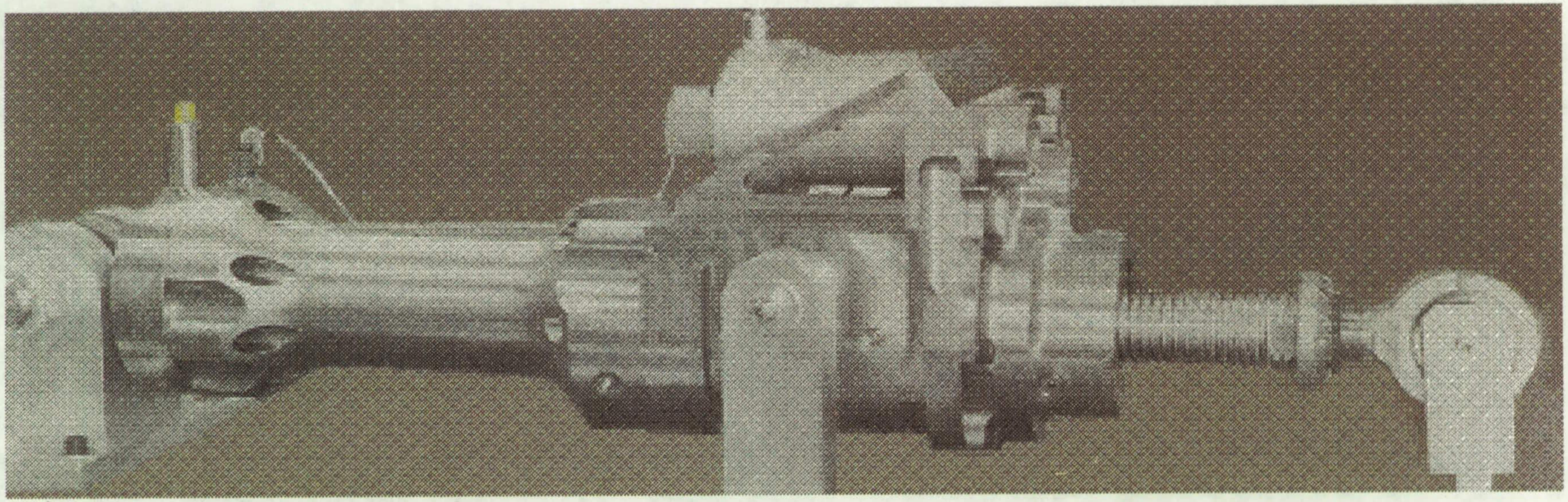
THREE-PHASE INDUCTION MOTOR BY SUNDSTRAND

ORIGINAL PAGE
COLOR PHOTOGRAPH

Lewis Research Center

POWER TECHNOLOGY DIVISION

LeRC 40 Hp ELECTROMECHANICAL ACTUATOR FOR THRUST VECTOR CONTROL APPLICATIONS



ELECTRONIC MOTOR DRIVE by GENERAL DYNAMICS SPACE SYSTEMS

INDUCTION MOTOR by SUNDSTRAND CORPORATION

MECHANICAL ACTUATOR by MOOG, INC.

GRS92-021.5

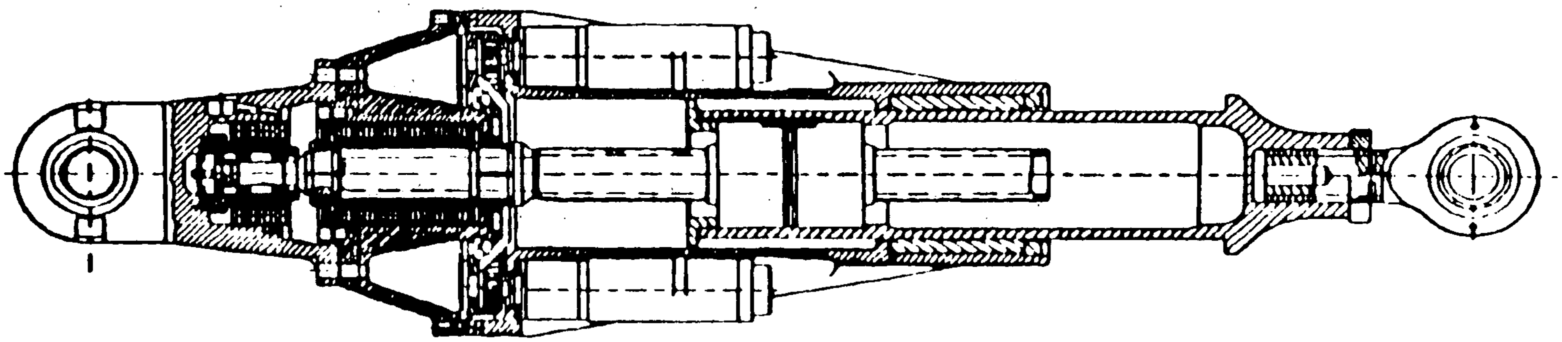
NASA

MSFC ADVANCED DEVELOPMENT PROGRAM

- **THRUST VECTOR CONTROL SYSTEMS**
  - DUAL CHANNEL 50 HP FEASIBILITY DEMONSTRATION UNIT
  - QUAD CHANNEL 60 HP SSME/SRB DEMONSTRATION UNIT
  - NLS TRIPLE- REDUNDANT DERIVED REQUIREMENTS AND SPECIFICATION

- **ENGINE CONTROL VALVE SYSTEMS**
  - MSFC SIMPLEX SSME MAIN OXIDIZER VALVE (MOV)
  - HR TEXTRON SSME MOV PROTO-FLIGHT UNITS
  - AEROJET STME PROPELLANT CONTROL VAVE UNITS

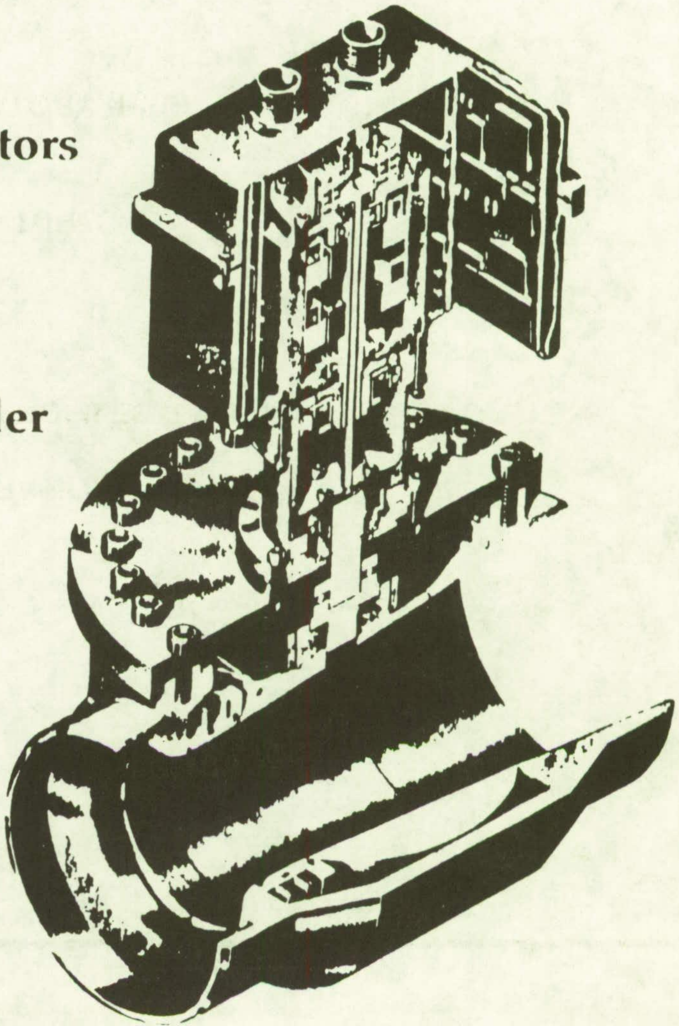
MSFC 60 Hp EMA Actuator With Quad Permanent Magnetic Motors



- 4 Channel 15 Hp Permanent Magnet DC Motors
- 9.6:1 Single Pass Gear Reduction w / 0.4 Inch Roller Screw Lead
- Rated Load of 60,000 Lbf
- Rated Velocity of 5 inch / sec
- Maximum Stroke of ± 5.25 inch
- 4.2 Hz Control Bandwidth

MSFC / Aerojet Main Engine EMA Propellant Valve Actuator

- Dual Redundant STME PVA
- Microcontroller Design w / BIT
- 0.485 Hp DC Permanent Magnet Motors
- 28 Volts 36 Amps Motor Controller
- 180:1 Harmonic Gear Reduction
- 7-9 Hz Control Bandwidth
- Internal Health Monitoring
- Reports its Status to Engine Controller



MSFC - CONTROL MECHANISMS & PROPELLANT DELIVERY BRANCH - EP64

NASA

EMA TEST FACILITIES AT MSFC:

- INERTIA LOAD SIMULATORS
  - SSME AND SRB TEST BEDS
  - SRB AND SSME COMMAND PROFILES
  - FLIGHT-TYPE (Ag-Zn) BATTERY OPERATIONS (FY - 93)
  - SRB FLIGHT LOADS AND COMMAND PROFILES (FY-93)
- RATE vs HYDRAULIC LOAD TEST BEDS
- ENGINE CONTROL VALVE FLOW TEST FIXTURES
- SSME HUNSTVILLE SIMULATION LABORATORY (HSL)
- SSME TECHNOLOGY TEST BED
- TEST STAND 116 CRYROGENIC FLOW FACILITIES

MSFC - CONTROL MECHANISMS & PROPELLANT DELIVERY BRANCH

NASA

MSFC_EMA TEST PROGRAM PARTICIPANTS:

- THRUST VECTOR CONTROL TEST ARTICLES (SSME & LOAD FIXTURES)
  - MSFC TVC SYSTEMS (DC PERMANENT MAGNET MOTORS)
    - DUAL 50 HP UNIT (TESTING IN PROGRESS)
    - QUAD 60 HP UNIT ASSEMBLY & CHECKOUT (AUGUST, 1992)
  - LeRC/GENERAL DYNAMICS DUAL REDUNDANT 60 HP INDUCTION MOTOR TVC (JULY, 1992)
  - HONEYWELL IRAD 30 HP TVC & VHM DEMONSTRATION (AUGUST, 1992)
  - MOOG IRAD TVC DEMONSTRATIONS (TBD)
  - BOEING/ ALLIED-SIGNAL TURBO-ALTERNATOR & ELECTRO-HYDROSTATIC TVC (SEPT. 1992)

- ENGINE CONTROL VALVES TESTING
  - MSFC SIMPLEX PROPELLANT VALVE ACTUATOR TESTING IN FLOW FACILITY AND HSL
  - HR TEXTRON MAIN OXIDIZER VALVE SSME QUALIFICATION TEST SERIES (JUNE, 1992 ATP)
  - AEROJET PROPELLANT VALVE ACTUATOR TESTING IN THE HSL (FY-93)

- SSME TECHNOLOGY TEST BED DEMONSTRATIONS (FY - 94)
  - MSFC QUAD 60 HP TVC
  - HR TEXTRON MOV

MSFC - CONTROL MECHANISMS & PROPELLANT DELIVERY BRANCH

ELECTRICAL ACTUATOR (ELA) /ELECTRO-MECHANICAL ACTUATOR (EMA) FEASIBILITY STUDY

Objective

- Determine the feasibility of replacing hydraulic/pneumatic actuators with ELAs in Ground Testing of Propulsion Systems to enhance operational efficiency of ground operations.
- Perform rigorous test program for ELA hardware evaluation prior to propulsion system and flight vehicle application and to gain early operational experience in a relevant environment.

Need

- Enhance operational efficiency and reliability of facility ground systems.
- Reduce the cost of labor intensive hydraulic systems in ground operations.

Approach

- Determine the applicability of EMA technology to support Static Test Firing of Rocket Engines and other test articles at SSC.
- Perform in-house testing to establish capabilities, reliability and cost effectiveness of replacing hydraulic/pneumatic actuators with Electrical Actuators.
- Coordinate SSC ELA activity with JSC, MSFC, LeRC and KSC.

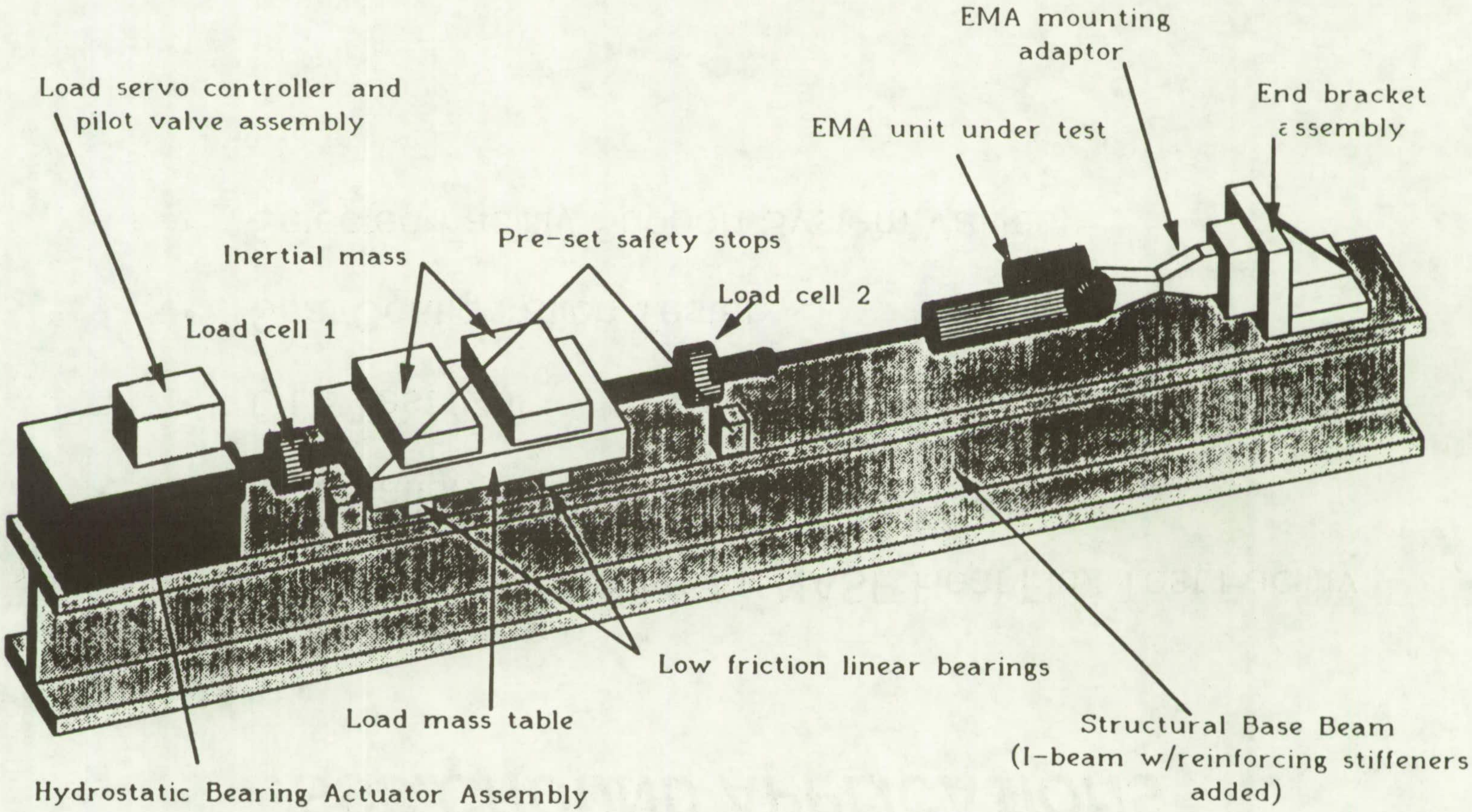
SSC GROUND APPLICATIONS

- Variable position valve for NASP Heat Flux Test Facility
- Automation of High Pressure Gas Facility
- CTF Test Cell
- Seal Configuration Tester
- Selected Facility Support System Valves

GW11101P19

NASA

JSC Electrical Actuation Test Facility



Electrical Actuation Technology Bridging

Lewis Research Center

SUMMARY

ELECTRICAL ACTUATORS CAN REPLACE HYDRAULICS IN LAUNCH VEHICLES

MAJOR ELECTRICAL ACTUATION ELEMENTS DEVELOPED, UNDER EVALUATION

TECHNOLOGY CAN PROVIDE STANDARDIZED, MODULAR TVC HARDWARE

ELECTRICAL ACTUATION ADVANCES COULD HELP U.S. COMPETITIVE POSITION

NLS Keynote speaker

Paper Not Available

C-2

Wright Laboratory

Power-By-Wire Flight Control Actuation Research & Development Activities

Presented By

Mr. David B. Homan
Wright Laboratory
WL/FIGS
Wright-Patterson AFB, OH 45433-6553
Phone: (513) 255-8679

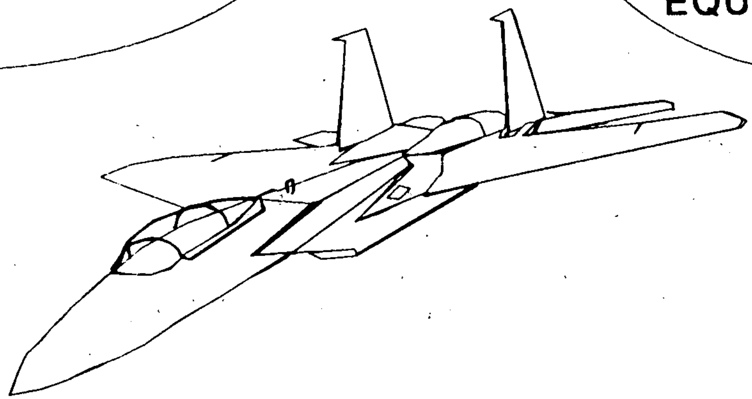
WHY Power-By-Wire?

EFFICIENCY

- POWER EXTRACTED FROM ENGINES
- HEAT MANAGEMENT

MAINTAINABILITY

- ELIMINATE HYDRAULIC DISCIPLINE
- LESS SUPPORT EQUIPMENT (AGE)



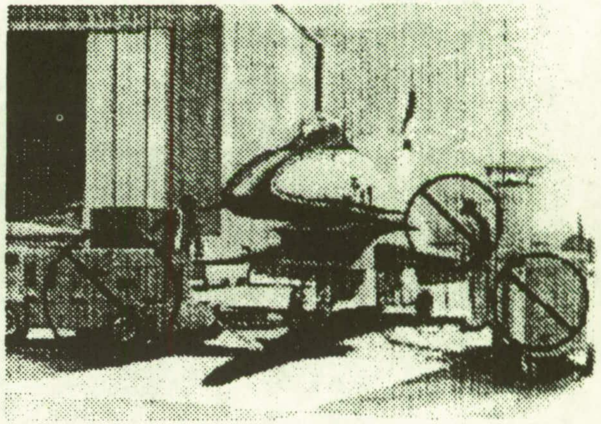
DESIGN IMPLICATIONS

- WEIGHT SAVINGS
- IMPROVED SURVIVABILITY
  - REDUCED VULNERABILITY
- SIMPLER SYSTEM

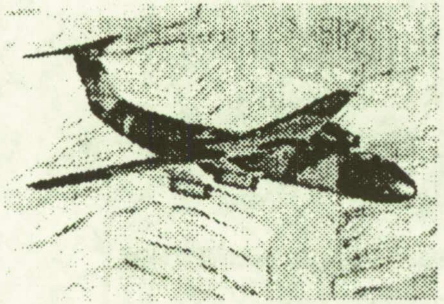
OPERATIONS

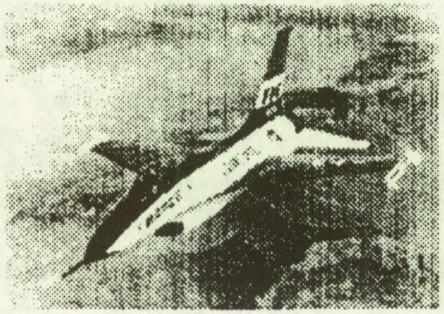
- HIGHER A/C SORTIE RATE
- LOWER LIFE CYCLE COSTS
  - MOBILITY
  - MANPOWER

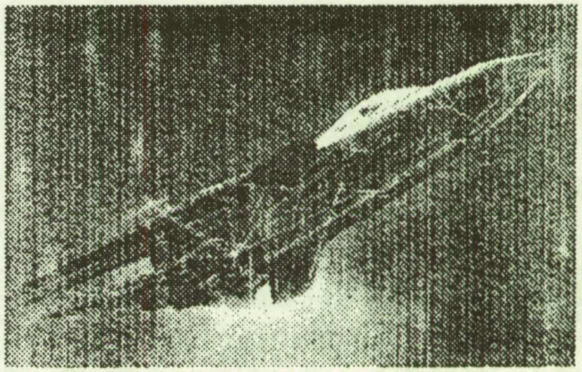
MORE–ELECTRIC AIRCRAFT

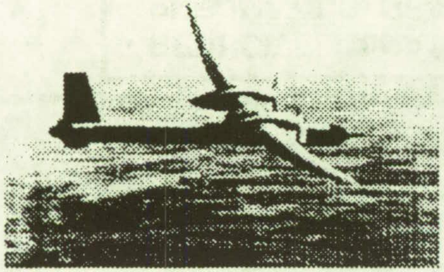


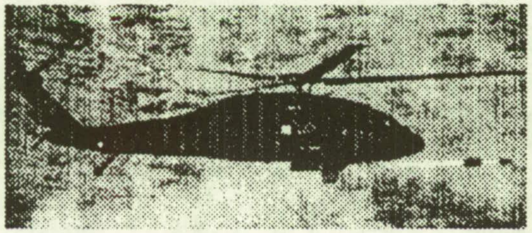
- FLIGHT LINE SUPPORT EQUIPMENT/ MAINTENANCE REDUCED BY MORE–ELECTRIC TECHNOLOGIES











- REPLACING CENTRALIZED HYDRAULICS WITH POWER–BY–WIRE OFFERS MAJOR SYSTEM LEVEL PAYOFFS

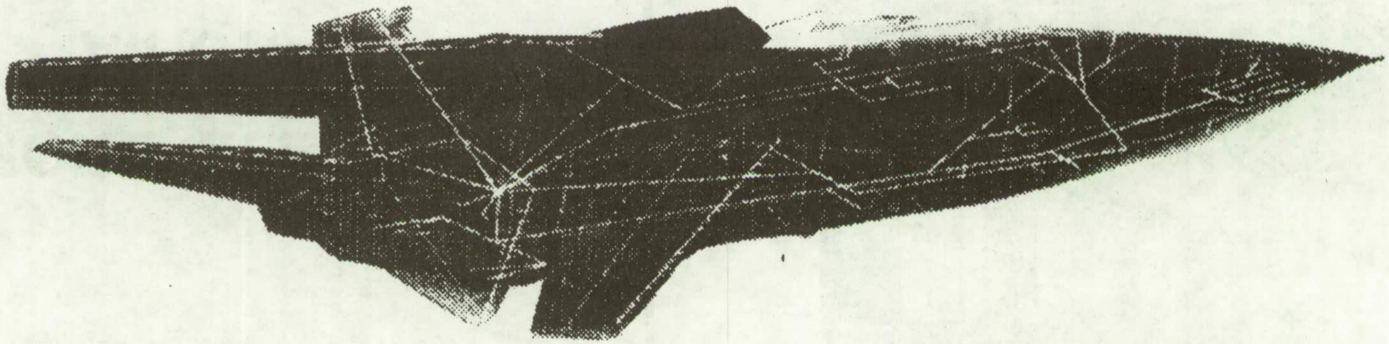
16206-

MORE ELECTRIC AIRCRAFT VISION

- REDUCE/ELIMINATE HIGH MAINTENANCE SUBSYSTEMS/DISCIPLINES (CENTRAL HYDRAULICS, BLEED PNEUMATICS, GEARBOXES, HAZARDOUS FLUIDS, AEROSPACE GROUND EQUIPMENT (AGE))

- FOCUS U.S. R&D EFFORTS IN AIRCRAFT POWER, SUBSYSTEMS AND ELECTRIC ACTUATION

- REDUCE LIFE CYCLE COSTS THROUGH IMPROVEMENTS IN COMPONENT RELIABILITY AND REDUCED O&S COSTS
- 30 TO 50% REDUCTION IN AEROSPACE GROUND EQUIPMENT (AGE)
- MAJOR SYSTEM LEVEL IMPROVEMENTS IN BATTLE DAMAGE TOLERANCE/MAINTAINABILITY/SUPPORTABILITY/VULNERABILITY
- ELIMINATE CENTRAL HYDRAULIC SYSTEM/HYDRAULIC MAINTENANCE/FIRE HAZARD
- IMPROVED AIRCRAFT PERFORMANCE FROM RESIZED ENGINES AND REDUCED WEIGHT
  – 600-1000#
- IMPROVED FLIGHT CONTROL, BRAKING, COOLING



E-0260 - 3

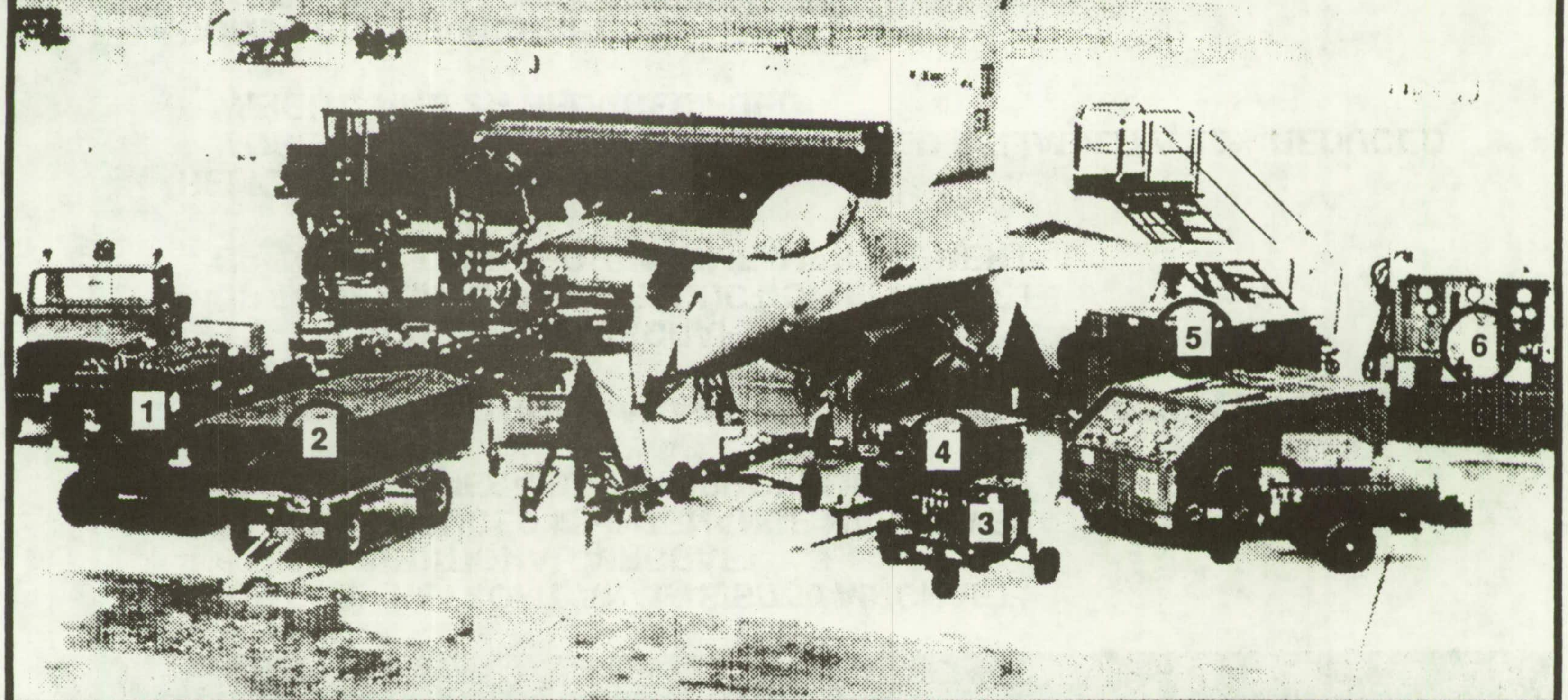
SYSTEM LEVEL PAYOFFS

[illegible] OF SYSTEM LEVEL PAYOFFS [illegible]

- FIGHTERS - RETROFIT ANALYSIS/750 AIRCRAFT
  - 60 - 129 ADDITIONAL AIRCRAFT
  - 11 - 15% REDUCED MAINTENANCE MANPOWER
  - 10 - 12% VULNERABILITY IMPROVEMENT
- TRANSPORT - RETROFIT ANALYSIS - ELECTRIC ACTUATION ONLY/267 AIRCRAFT
  - 3.3 - 5.9 ADDITIONAL AIRCRAFT
  - UP TO 182 MANPOWER REDUCTION PER FLEET
  - UP TO 58% TURNAROUND TIME IMPROVEMENT
- HELICOPTERS
  - MORE ELECTRIC ENGINE -15% IMPROVED RELIABILITY, 22% REDUCED WEIGHT, AND 2% REDUCED FUEL
- COMMERCIAL AIRCRAFT
  - MORE THAN 2% FUEL SAVINGS

16022- 3

REDUCE SUPPORT EQUIPMENT REQUIREMENTS



1. Electric Generator
2. Hydrazine Servicing Cart
3. Hydraulic Servicing Cart
4. High Pressure Air Cart
5. Air Conditioner
6. Hydraulic Mule

Flight Line Battery Support Shop (Not Shown)

16 C-141s Required to Support 24 F-16s

POWER-BY-WIRE
FLIGHT CONTROL ACTUATION

Wright Lab Funded Programs

- *Electrically Powered Actuation Design (EPAD) Validation Flight Test Program*
- *ElectroHydrostatic Actuation (EHA) for Large Aerodynamic Surface Applications*
- *C-141 Electric Starlifter Power-By-Wire Reliability & Maintainability Flight Test Program*
- *Flight Control Systems Actuation Technology*
- *Switch Reluctance Motor Development*

POWER-BY-WIRE FLIGHT CONTROL ACTUATION

Other Wright Lab Activities

- ***Supporting Lockheed HTTB PBW Flight Tests***
  - OC/ALC & Parker Aileron EHA Demo
  - Lucas Rudder IAP Demo
- ***Support Focusing IRAD for PBW Development***
- ***Plan Stabilator Actuator Flight Test Demo***
  - FIGS Electric Stab Act'r Program
  - MEA Secondary Power + Electric Stab Act'r
- ***Plan PBW Flight Control System Demo***
  - More Electric Aircraft Ground/Flt Tests
  - More Electric AFTI F-22 Demonstrator
- ***Plan Rotary/Thin Wing PBW Actuator Dev***

POWER-BY-WIRE FLIGHT CONTROL ACTUATION

1990 Technology Assessment

CAPABILITY

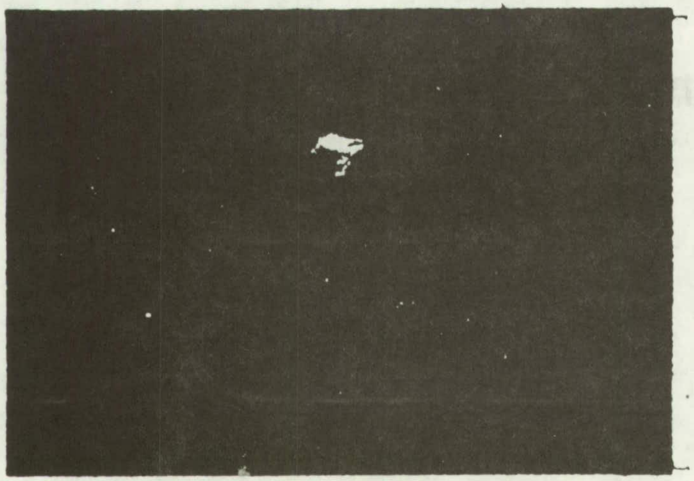
- Moderate Horsepower, Low Power Density
  - ✓ 3-5 HP
  - ✓ 1-3 HP/Ft^3
  - ✓ 10,000-15,000 LbF
  - ✓ 4-6 In/Sec
  - ✓ 1-3 Hz

LIMITATION

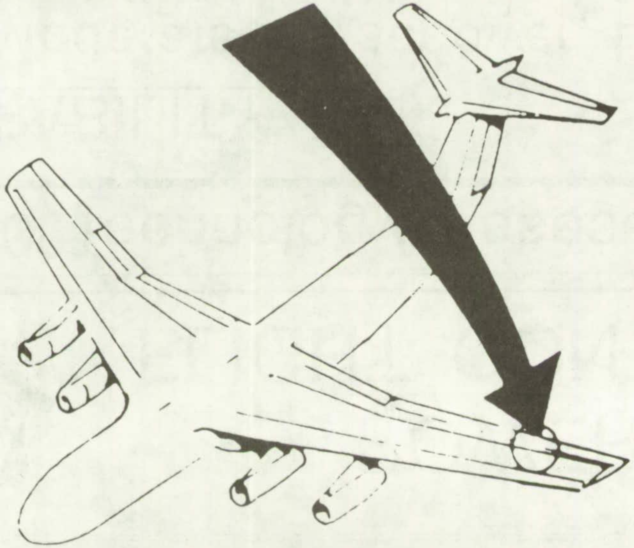
- Only Trailing Edge Surface Applications
- Transport Class Aircraft

RISK

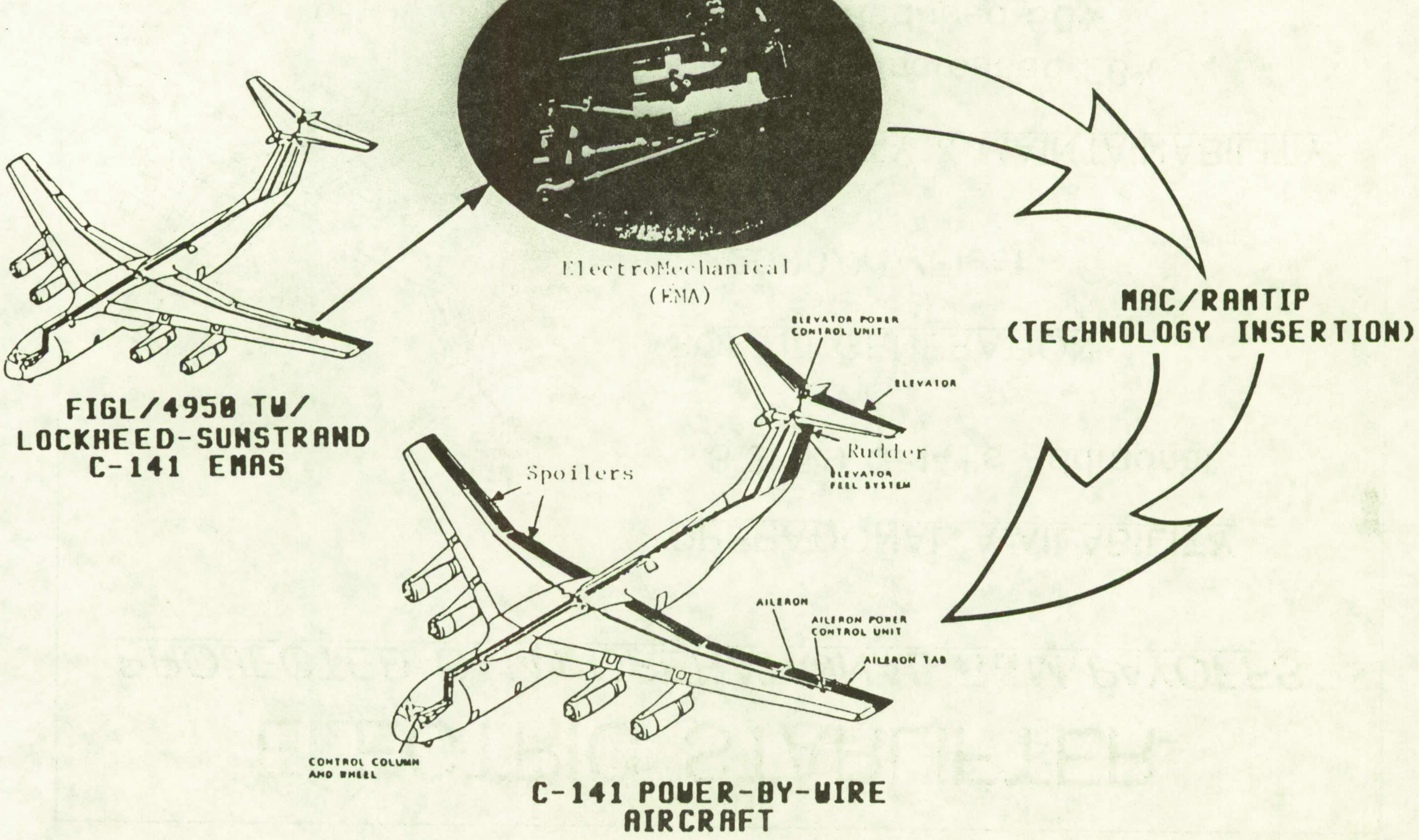
- PBW for Fighter Surface Application
- EHA from Lab Tests to Flight Tests



- HYDRAULIC POWER SOURCE ELIMINATED
- DUAL POWER REDUNDANCY
- PRIMARY CONTROL SURFACE APPLICATION

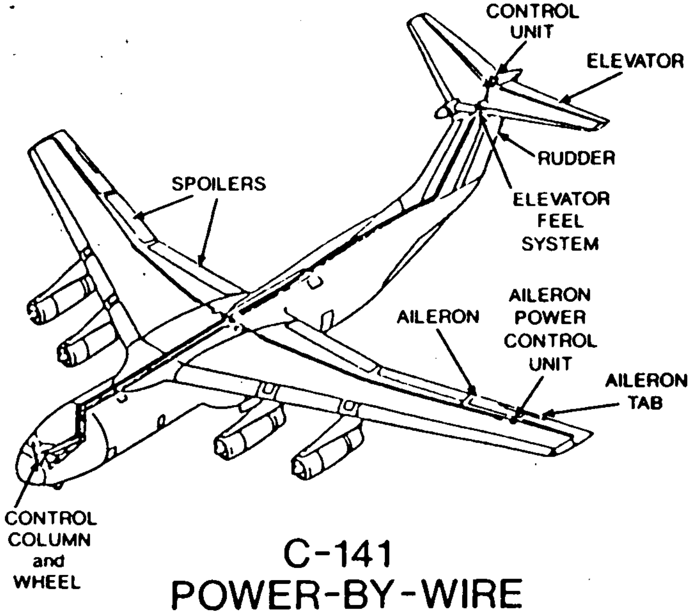


THE ELECTRIC STARLIFTER RAMTIP PROJECT #8817



ELECTRIC STARLIFTER

PROJECTED C-141 OPERATIONAL R&M PAYOFFS



C-141
POWER-BY-WIRE
AIRCRAFT

OPERATIONAL AVAILABILITY

3.3-5.9 C-141's Additional

SORTIE GENERATION

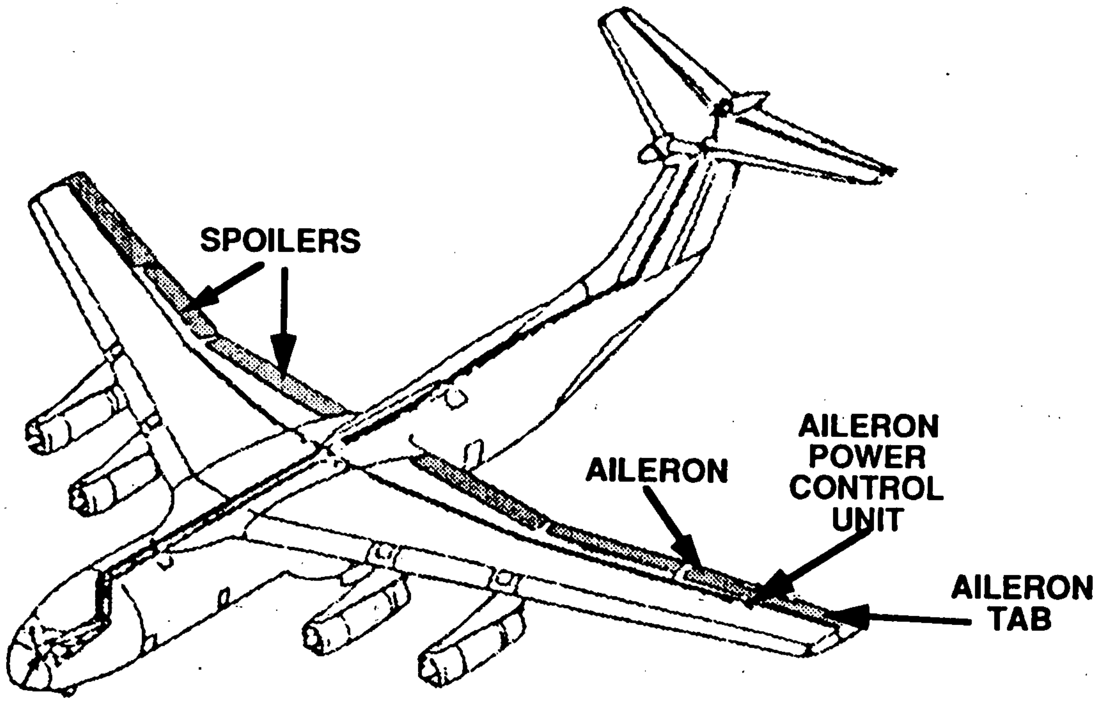
+2000/YR/Fleet

RELIABILITY & MAINTAINABILITY

MTBMA Increased 28%
MTTR Reduced 50%
MMHrs/A-C/Yr Reduced 55%
2 Level Maint
Troubleshoot Time Cut 83%

ELECTRIC ACTUATION

- C-141 ELECTRIC STARLIFTER -- DEMONSTRATE THE R/M/S OF ELECTRIC ACTUATION IN OPERATIONAL ENVIRONMENT (2X RELIABILITY, LRU CONCEPT, 16 ACTUATORS)



**C-141
POWER-BY-WIRE
AIRCRAFT**

FIRST FLIGHT - 4QFY94

DELIVERY TO AMC 1QFY95

E-0248 - 7

POWER-BY-WIRE FLIGHT CONTROL ACTUATION

1993 Technology Assessment

CAPABILITY

- Moderate Horsepower, Moderate Power Density
  - ✓ 5-7 HP
  - ✓ 15-25 HP/Ft^3
  - ✓ 15,000-20,000 LbF
  - ✓ 4-6 In/Sec
  - ✓ 4-7 Hz

LIMITATION

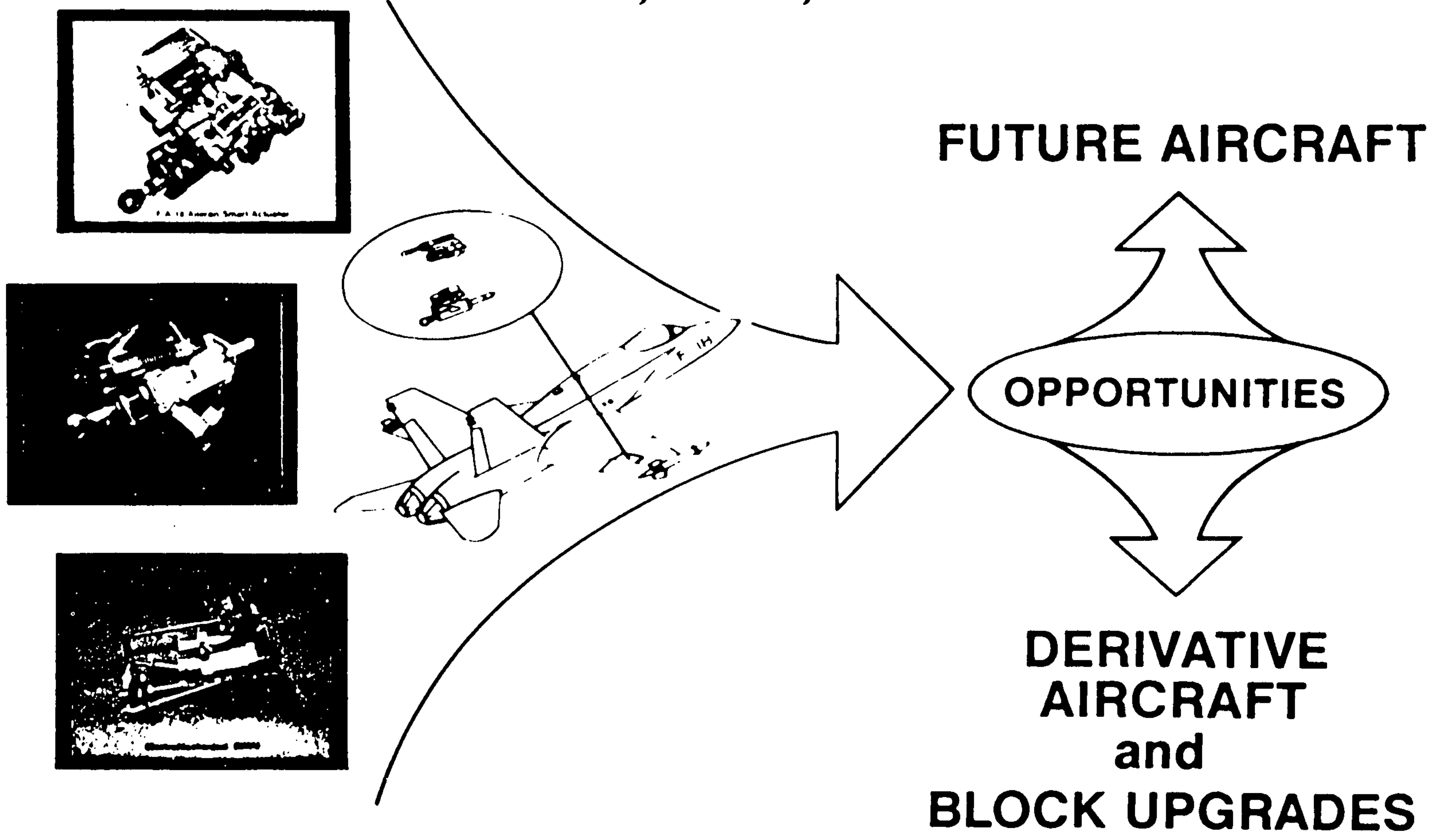
- Only Trailing Edge Surface Applications
- Transport & Fighter Aileron/Rudder

RISK

- High HP PBW Act'r for Stiffness Driven Surface (i.e. Horizontal Stabilator, Elevator, Canard)

ELECTRICALLY POWERED ACTUATION DESIGN (EPAD) VALIDATION PROGRAM

JOINT AF, NAVY, NASA PROGRAM

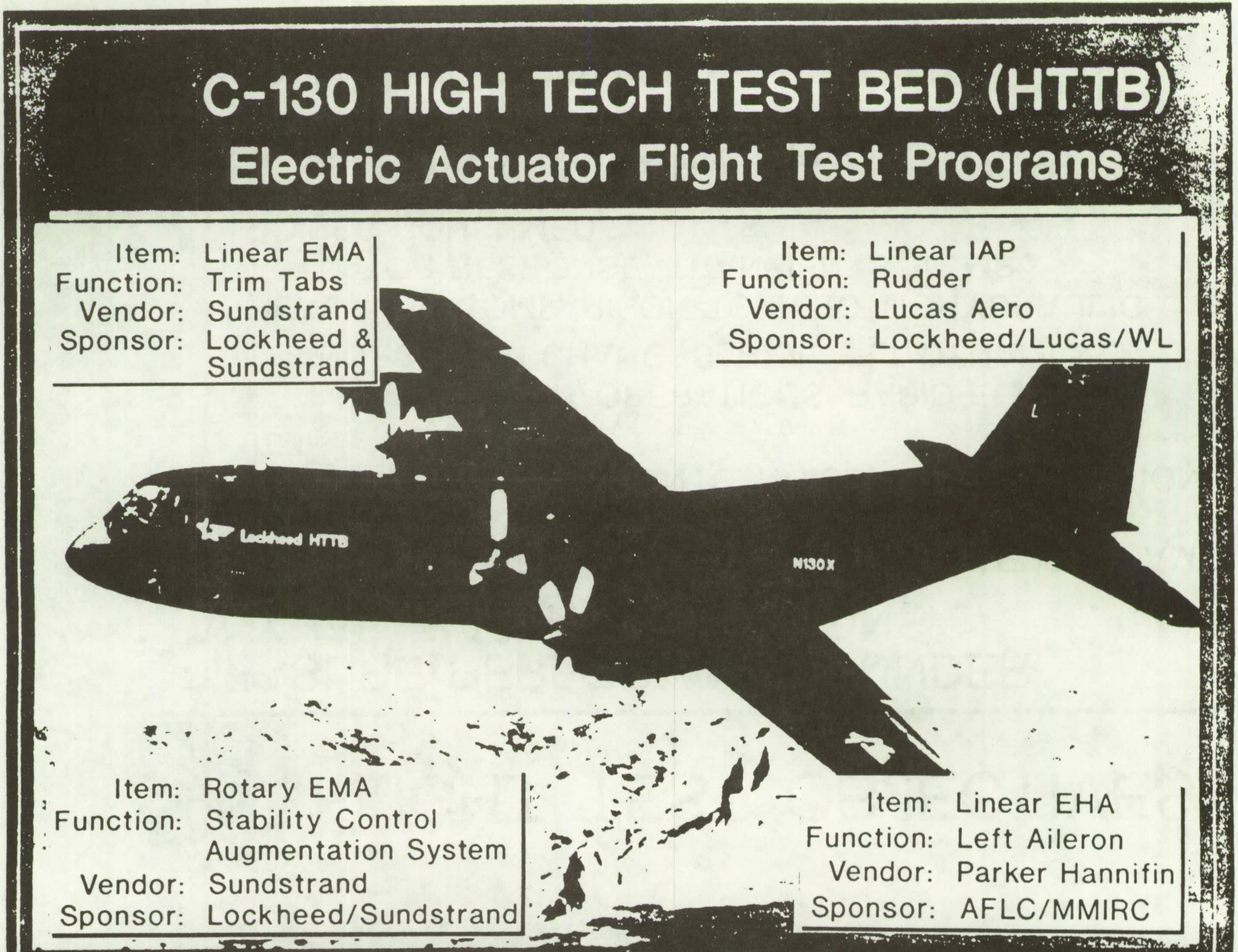


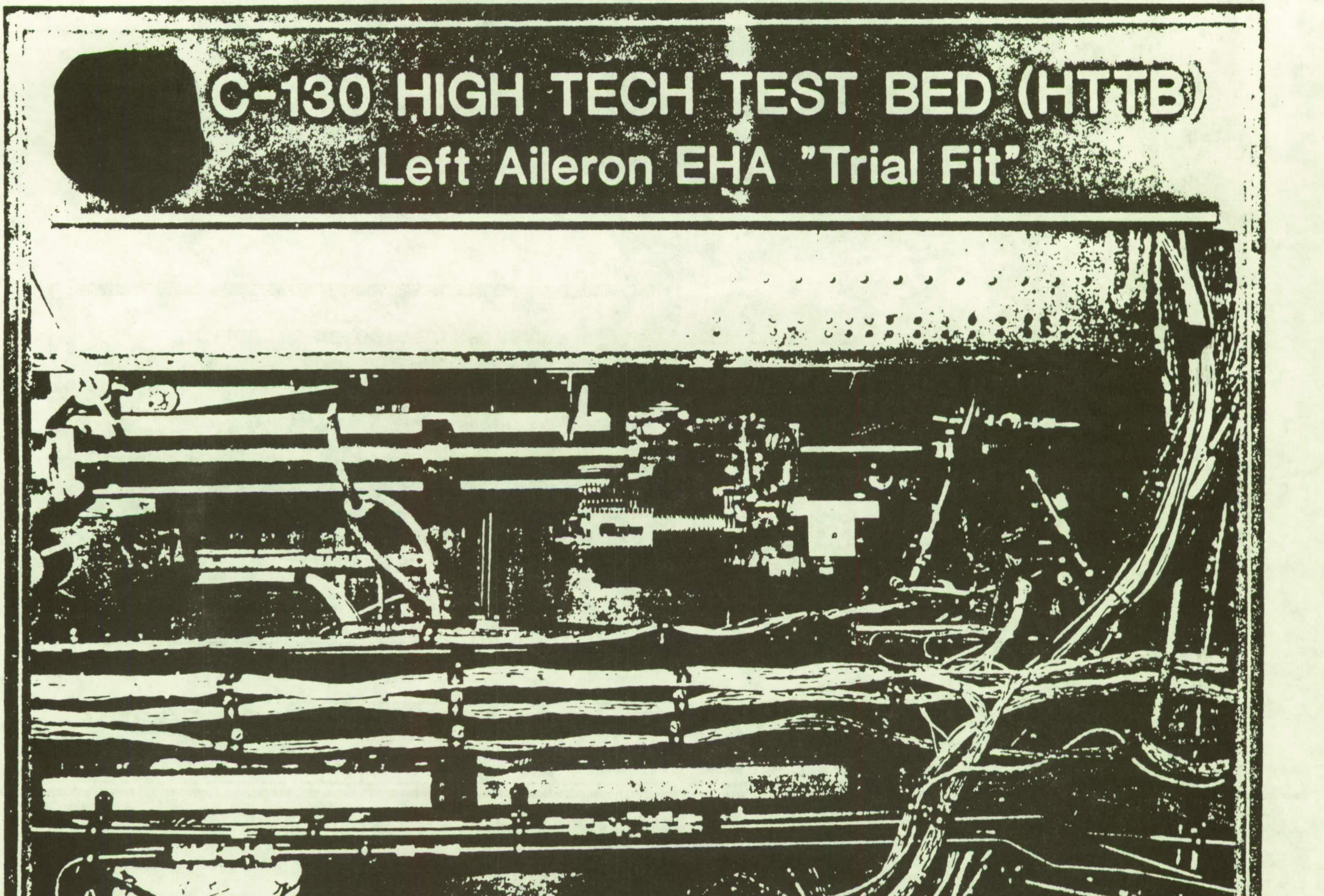
GOALS OF EPAD

- FLIGHT TEST DEMONSTRATE PBW TECHNOLOGY ON PRIMARY FLIGHT CONTROL SURFACE ON A FIGHTER A/C
- TRANSFER PBW TECHNOLOGY TO INDUSTRY AND OTHER GOV AGENCIES
- BASELINE PROGRAM FOR MEA
- BASELINE INFORMATION FOR NAVY A/X PROGRAM

FLIGHT TEST OBJECTIVES

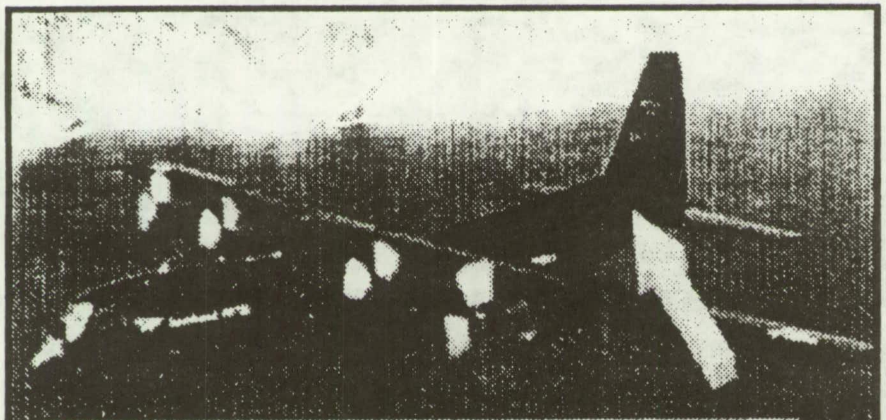
- MEASURE PERFORMANCE UNDER ACTUAL FLIGHT CONDITIONS
  - ✓ COMBINED LOADS (SURFACE): INERTIAL, AERODYNAMIC AEROELASTIC
  - ✓ COMBINED ENVIRONMENTS: NOISE, TEMP, VIBRATION EMI
  - ✓ REAL MANEUVERS/OPERATIONS: RAPID FLT CHANGES, TRIM CHANGES, REAL FLT DYNAMICS
  - ✓ REAL TIME COMPARISON TO ELECTROHYDRAULIC ACTUATOR RESPONSE, TRANSIENTS, TEMP POWER CONSUMED
- SEARCH FOR UNEXPECTED
- DOCUMENT RESULTS


C-130 HIGH TECH TEST BED (HTTB)
Electric Actuator Flight Test Programs
Item: Linear EMA
Function: Trim Tabs
Vendor: Sundstrand
Sponsor: Lockheed & Sundstrand
Item: Linear IAP
Function: Rudder
Vendor: Lucas Aero
Sponsor: Lockheed/Lucas/WL
Lockheed HTTB
N130X
Item: Rotary EMA
Function: Stability Control Augmentation System
Vendor: Sundstrand
Sponsor: Lockheed/Sundstrand
Item: Linear EHA
Function: Left Aileron
Vendor: Parker Hannifin
Sponsor: AFLC/MMIRC


C-130 HIGH TECH TEST BED (HTTB)
Left Aileron EHA "Trial Fit"

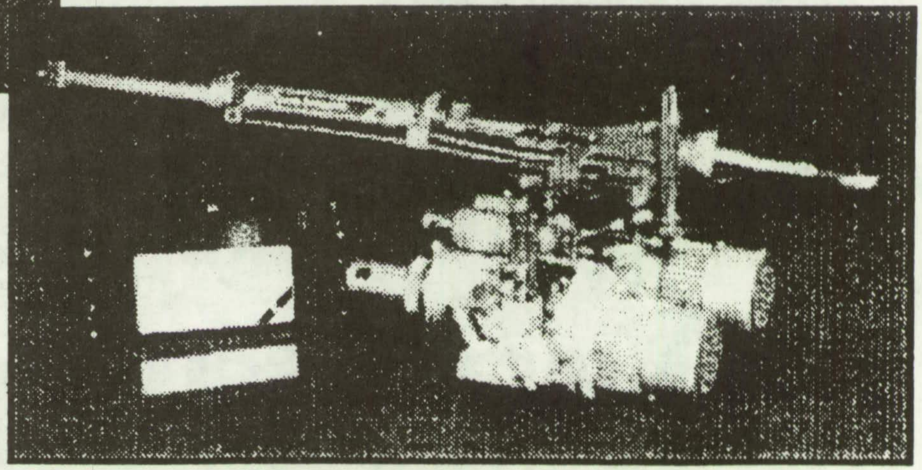
ELECTRIC ACTUATION

- **INTEGRATED ACTUATION PACKAGE FOR HTTB RUDDER SUCCESSFULLY DEMONSTRATED**



LOCKHEED'S HIGH TECHNOLOGY TEST BED AIRCRAFT (HTTB)

FULLY REDUNDANT, POWER-BY-WIRE ACTUATION SYSTEM
- 115 VAC POWERED
- 5750 LBS MAX OUTPUT FORCE
- 4 HZ ± 2% NO LOAD FREQUENCY RESPONSE
- DIGITAL ELECTRONIC PUMP CONTROL UNIT (ECU)
- ADAPTABLE FOR FLY-BY-LIGHT



E-0248 - 6

POWER-BY-WIRE FLIGHT CONTROL ACTUATION

1996 Technology Goals

CAPABILITY

- High Horsepower, High Power Density
  - ✓ 15 - 35 HP
  - ✓ 20-25 HP/Ft^3
  - ✓ 30,000-55,000 LbF
  - ✓ 7-20 In/Sec
  - ✓ 7-15 Hz

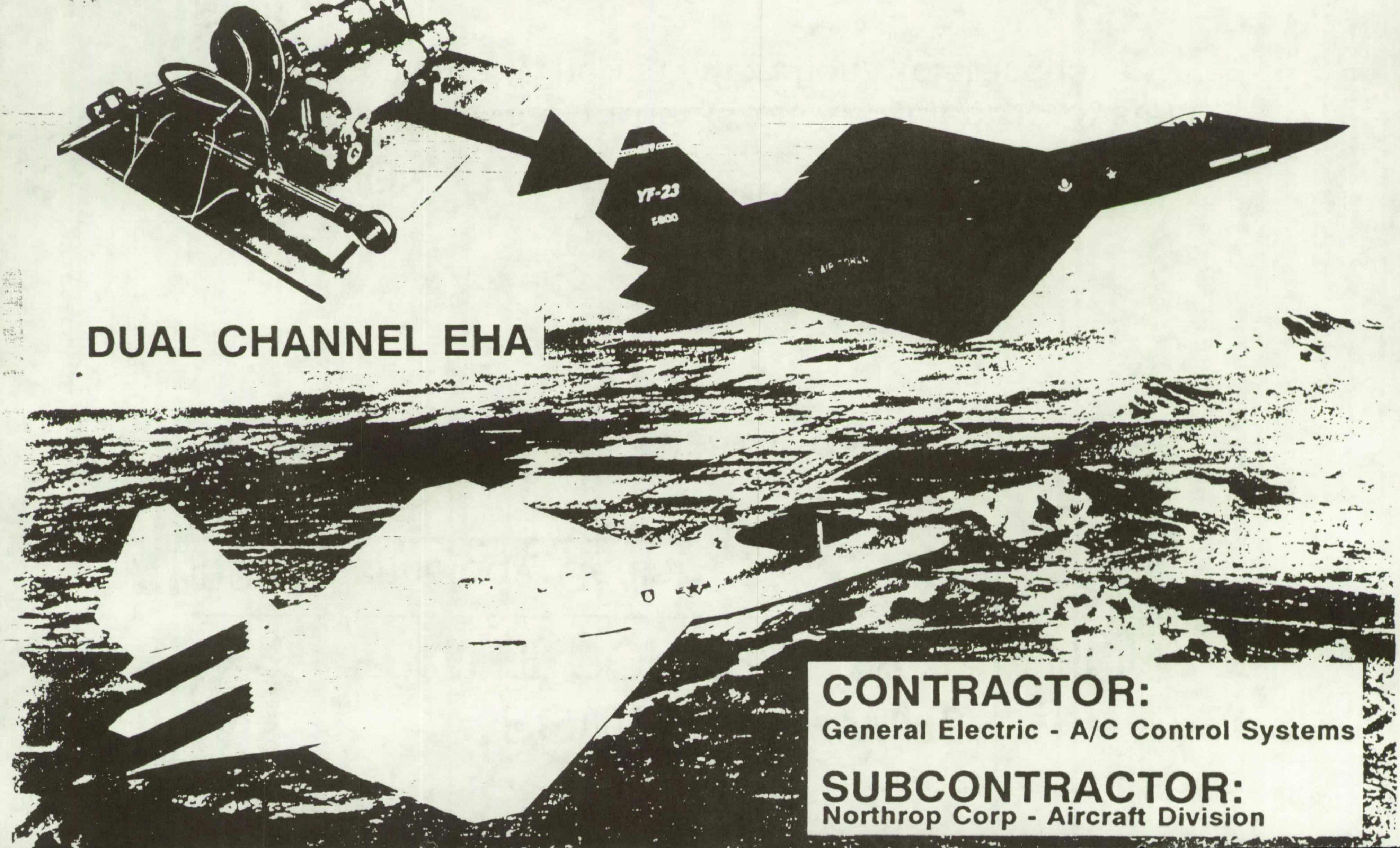
LIMITATION

- PBW Act'n System Effects on A/C Electric System
- Environmental (Thermal/Vibration) Tolerances

RISK

- PBW Act'r Embedded Fault Tolerance
- No PBW Flight Control Actuation Sys Ground/Flt Test

ElectroHydrostatic Actuator (EHA) for Large Aero Surface Applications



ELECTROHYDROSTATIC ACTUATOR (EHA) For LARGE AERO SURFACE APPLICATIONS

OBJECTIVE

Develop EHA System Capable of Meeting A Fighter Flight Critical Surface Performance AND Control & Power Redundancy Management Requirements

- Select Critical Surface Application *(YF-23)*
- Trade Study System & Subsystem Technologies
- Design EHA System Using Trade Results
- Develop EHA Subsystems & Test
- Build EHA System Via Subsystems Integration
- Laboratory Test EHA System
- Verify System & Subsystem Models
- Document Results

ELECTROHYDROSTATIC ACTUATOR (EHA) For LARGE AERO SURFACE APPLICATIONS

PURPOSE

Expand Power-By-Wire Actuator Technologies To Include Large, Flight Critical Surface Applications

- Expand PBW Act'n Performance to Flight Control Extreme
  (EHA/EMA - Fighter Aileron, IAP/EMA/EHA - Transport Aileron)
  (2-3X Higher Force/Rate, 4-6X Higher HP)
- Provide Tech Base for Future Flight Test Demo
  (More Electric Stabilator Actuator - Proposed 6.3)
- Provide Opportunity to Address & Answer Redundancy Management Issues & Implement into A Design
- Provide Electrical Power Loads, Distribution & Management Requirements to MADMEL (WL/POO)
  (Management And Distribution of More ELectric Power - 63216)
- Impact More Electric Airplane Critical Technology List

POWER-BY-WIRE FLIGHT CONTROL ACTUATION

Wright Lab Funded Programs

- *Electrically Powered Actuation Design (EPAD) Validation Flight Test Program*
- *ElectroHydrostatic Actuation (EHA) for Large Aerodynamic Surface Applications*
- *C-141 Electric Starlifter Power-By-Wire Reliability & Maintainability Flight Test Program*
- *Flight Control Systems Actuation Technology*
- *Switch Reluctance Motor Development*

FLIGHT CONTROL SYSTEMS ACTUATION TECHNOLOGY

JON: 24030748

PURPOSE

(Why Are We Doing This?)

- Provide Actuation Technology for Current & Future Military Aircraft Which is Simpler and/or Less Expensive Than Current State of the Art

- Provide Tech Integration & Test for EPAD Actuators (EHA, EMA & Smart) with Electrical Power, FCC & Aero Space on NASA F/A-18 Testbed

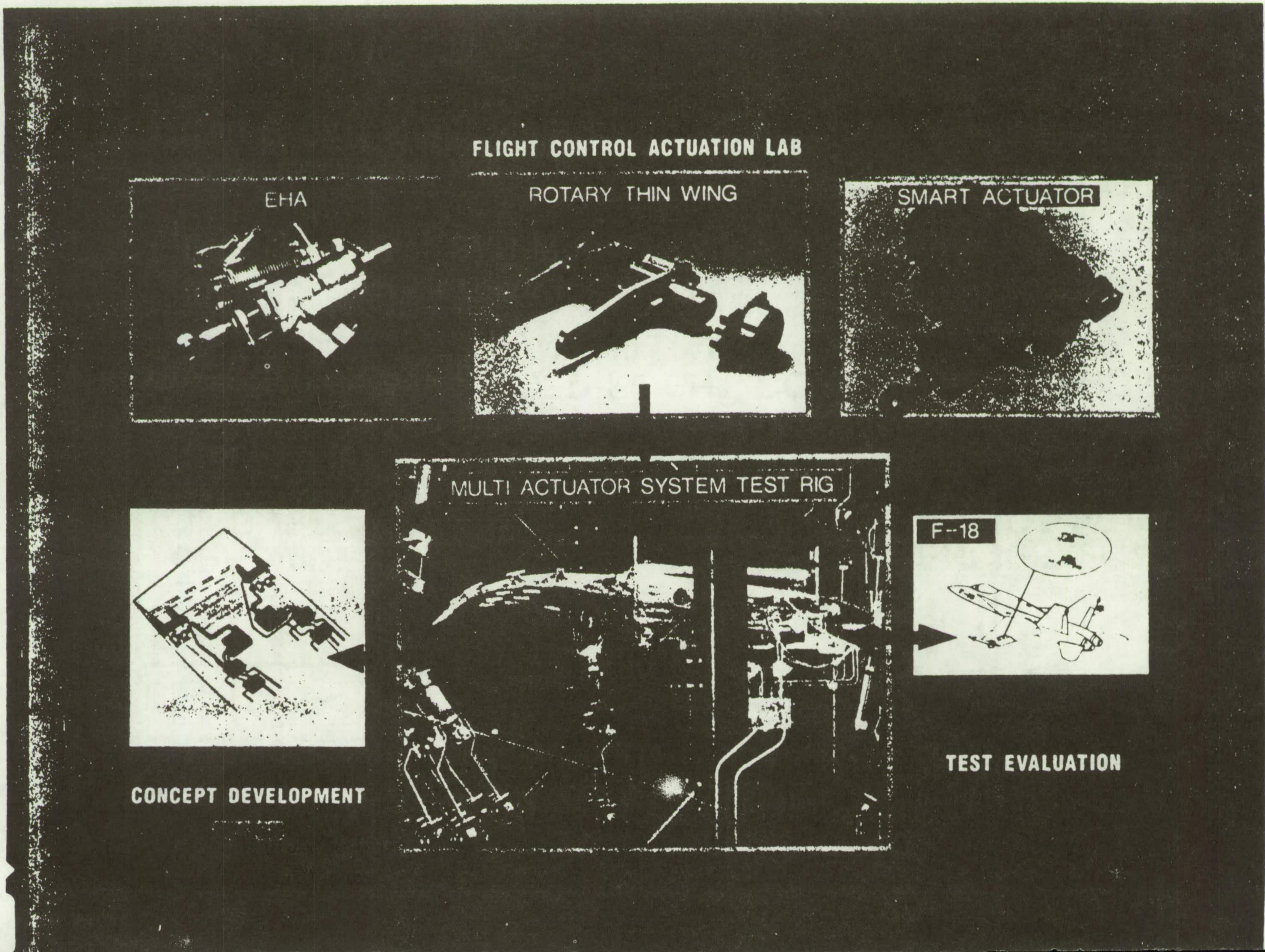
- Provide Flight Control Actuation Support to Ongoing Wright Laboratory Programs
  - *WL/FIG (EPAD, VISTA, LAMARS)*
  - *WL/MLB (NON-FLAMMABLE FLUID)*

FLIGHT CONTROL SYSTEMS ACTUATION TECHNOLOGY

JON: 24030748

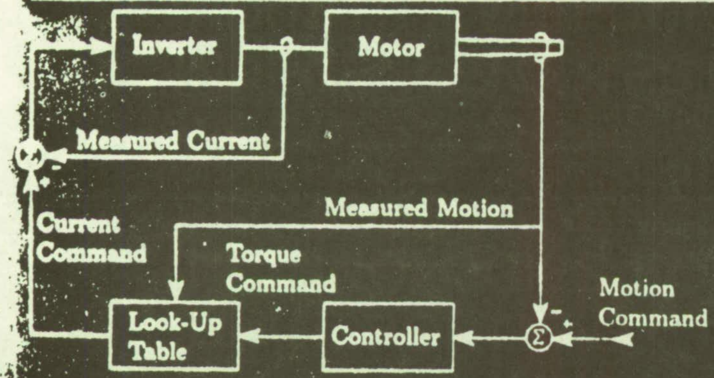
BENEFITS

- PROVIDES AF, OTHER DoD & GOV'T AGENCIES, and INDUSTRY with UNIQUE FLIGHT CONTROL ACTUATION INDEPENDENT TEST & EVALUATION CAPABILITY
- PROVIDES ADVANCED FLIGHT CONTROL ACTUATION TECHNOLOGIES FOR MILITARY & COMMERCIAL TRANSPORTATION APPLICATIONS
- GIVES WRIGHT LAB CREDIBILITY AS ACTUATION VOICE
- MAKES A GREAT TOUR STOP IN WRIGHT LAB!


FLIGHT CONTROL ACTUATION LAB
EHA
ROTARY THIN WING
SMART ACTUATOR
MULTI ACTUATOR SYSTEM TEST RIG
F--18
CONCEPT DEVELOPMENT
TEST EVALUATION

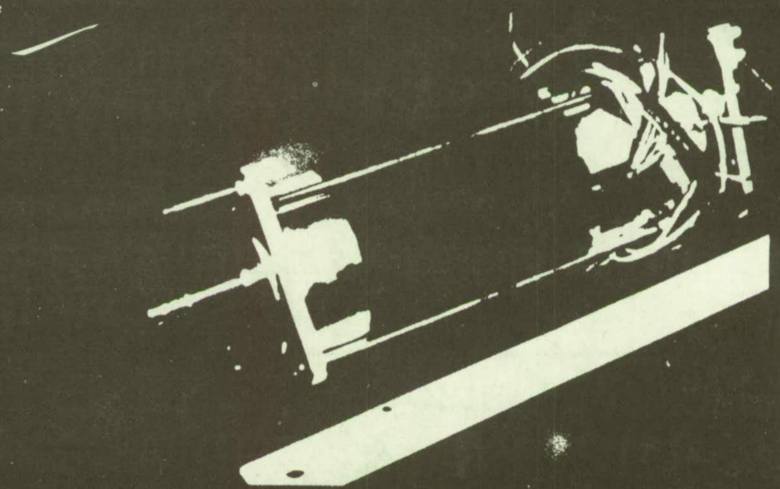
SWITCHED VARIABLE RELUCTANCE (SVR) MOTOR FOR ELECTRIC ACTUATION

Mr David Homan, WL/FIG DSN 785-8679



RESEARCH ISSUES

- Power Requirements
- Force, Rate, Torque
- Thermal Environment
- Fly-By-Wire Control
- Fault Tolerance



PRINCIPAL INVESTIGATOR:
Massachusetts Institute of Technology - Lincoln Laboratory

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SWITCHED VARIABLE RELUCTANCE (SVR) MOTOR FOR ELECTRIC ACTUATION

Mr David Homan, WL/FIGL, DSN 785-8679

RESEARCH ISSUES

- Can A SVR Motor Meet Flight Control Requirements for Actuator Force, Rate, Torque & Environment?
- Develop & Test SVR Motor to Verify Capabilities & Identify Inefficiencies for Further R&D

BENEFITS/PAYOFFS

- Contributes to "More Electric" Aircraft Technology Base
- Simpler & More Robust than Current AC & DC Motors
- Provides Alternative to Current State-of-the-Art AC & Brushless DC Motor Driven Actuators.

POWER-BY-WIRE FLIGHT CONTROL ACTUATION

IN SUMMARY...

- Wright Laboratory Control Systems Development & Applications Branch (WL/FIGS) Is A Technology Leader In Flight Control Actuation Development
- Power-By-Wire Actuation Is The Technology That Makes A More Electric Airplane Feasible
- Inhouse & Contracted Efforts Underway to Expand PBW
- Planning Activities Underway For Future PBW Work
- Supporting Users & Industry To Transition Tech

SESSION II

ELA SYSTEMS METHODOLOGY

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ELA/EMA Control with Resonant Power Processors

Jim Mildice

JWM - 1

September, 1992

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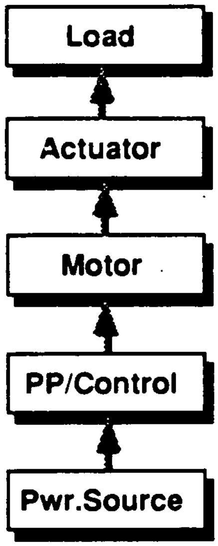
ELA/EMA System Elements



- **Fixed force + inertia + rates + acceleration - set primary requirements**
- **Rotary to linear conversion + gear train for speed matching**
- **Prime mover - electrical to mechanical conversion** (several AC technologies available)
- **Control of motor speed, direction, and output torque**
- **Energy storage** (battery) **or conversion** (machinery) **elements**

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September, 1992

The system in this discussion is a large servo-type hardware and software assembly typically found in large launch vehicle TVC applications, or aerosurface control of large aircraft. It can be broken into major elements according to the block diagram above.

The load is defined by the steady-state forces required to provide the actual movement and the acceleration of the inertias of the masses to be moved. The dynamic responses are defined by the vehicle dynamics and the external forces acting on the vehicle. Loads are typically in the 25,000- to 50,000-pound range for an NLS-2 class vehicle.

Because of the short time allocated for this discussion, we have decided to provide a summary of General Dynamics conclusions about the actuator, motor, and power processing and control elements of the block diagram, along with the most important reasons for those choices. There have been detailed presentations and demonstrations about these elements, with full justifications for the selections. If you wish any of that data, please refer to the Bibliography and the end of this data package.

Many power source options are available. because of high peak loads, they are usually sized by the system peak power demands, and technologies having high specific power rather that high specific energy are desirable. The choice between batteries and rotating machines is usually driven by operations and test considerations.

This presentation will then focus on, and discuss the most important considerations driving ELA/EMA system design, system inertias and how they drive the entire configuration and its capability.

Actuator

- **Three primary system choices**
  - Ballscrew technology is well-established
  - Rollerscrew technology has some performance advantages
  - Electro-hydrostatic actuators are available where the "softness" of hydraulics is still required
- **Motor and gear train inertia is the most important mechanical parameter for TVC applications**
  - Normal gear reductions isolate the load inertia
  - Design for maximum power transfer makes desirable for the two inertias to be about equal
  - These inertias are the primary driver for peak input power requirements
    - They size the power processor/motor controller
    - They determine the energy source size and character

Even though the required motions for most ELA's are rotary (engine rotation about its gimbal point, control surface rotation about its root, etc.), vehicle physical limitations and form factors usually require that the load be moved by a linear thrust. The actuator provides the conversion from rotary motor input to linear output thrust. Rotary power requirements can typically be between 25- and 75-horsepower for our applications.

Three primary rotary-to-linear thrust mechanisms under current use and consideration are listed above. The mechanical "screw" technologies are straight forward.

Electro-hydrostatic, sealed, self-contained, single-actuator hydraulic systems can be mechanically simple and solve many of the present distributed hydraulic system operability, leak, and contamination problems. Since the motors and controllers that drive them are very much the same whether or not variable speed and direction control are included, the most efficient overall system design uses a variable- speed/direction controller, motor, and hydraulic pump, and eliminates the complexities of servo valves, force amplifiers, and other fluids hardware.

It's easy to design a small, high-speed motor/gear train system to drive the steady-state load, and the resulting large-ratio gear system also reduces the reflected usual load inertias so that they become small when compared to other inertias in the system. That means that the motor and gear train inertias dominate the power requirements for inertia acceleration and bandwidth, and the peak power input and peak-to-average ratio are fully under the TVC system designer's control.

Motor Type Characteristics

Common Name	Stator Power	Rotor Power	AC Syntheses
• "Classical" DC	DC	AC, sq. wave	Sliding contact, mechanical, rotary switch (commutator)
• "Classical" DC (permanent magnet)	Magnet	AC, sq. wave	Sliding contact, mech, mechanical, rotary switch (commutator)
• "Brushless DC" (permanent magnet)	AC	Magnet	External electronic switch
• AC Induction	AC	Magnetically-coupled low-frequency, AC	AC power source or external electronic switch
• AC Synchronous	AC	AC, DC, or permanent magnet	AC power source or external electronic switch
• Switched Reluctance	Sequenced Pulses	None - rotor is magnetic iron	External electronic switch

JWM - 4 September, 1992

Motors used in modern systems are all AC types, often interfaced to DC power systems with power processors to provide the appropriate input waveforms. The make up a class of so-called "brushless DC" motors which can include any type of AC prime mover. Well-designed motors and actuators for these applications typically require 25- to 50-horsepower for the constant load, and an equal amount of power for acceleration of inertias.

The "classical DC" motors shown above are commutator types. The significance of this configuration is that not even this age-old DC motor actually has DC in the internal fields that cause it to rotate. Its rotor current is actually square-wave AC created by a mechanical reversing switch. That reversing switch has a sliding contact system, mounted on the motor output shaft, and is made up of a "commutator" and brushes.

The development of good power semiconductor switches and high-field magnetic materials allowed a design which eliminated the commutator and brushes. It placed the constant field (produced by a magnet) on the rotor, and switched the alternating AC field to the stator with external switch networks, and we had the so-called "brushless DC" motor; really nothing more than a permanent magnet AC motor with an external switched, multi-phase inverter. When we supply this same motor AC from the power system instead of DC, we eliminate the switches and call it a permanent magnet AC motor, a small version of which we can find in analog electric clocks.

AC induction motors also eliminate the commutator and brushes, and supply power to create the magnetic field on the rotor through transformer action. The transformer frequency is the difference between the rotating magnetic field supplied by the stator and the actual speed on the rotor (the "slip").

Switched reluctance motors use external switches to create a rotating magnetic field from the stator in the same way as the original "brushless DC" permanent magnet design. However, a notched, soft iron rotor replaces the permanent magnets, and it follows the rotating field when the magnetic forces try to minimize the reluctance of the magnetic path, in a way similar to a stepping motor.

Control Parameter Comparison

Common Name	Torque	Speed	Remarks
• "Classical" DC	No independent control of torque and speed		Input voltage controls output power
• "Classical" DC (permanent magnet)	No independent control of torque and speed		Input voltage controls output power
• "Brushless DC" Permanent Magnet	Input voltage	Frequency	External electronic switch network synthesizes variable-voltage, variable-frequency inputs to mimic classical DC performance
• AC Induction	Slip (rotor freq), Input voltage	Stator frequency & slip	External electronic switch network synthesizes variable-voltage, variable-frequency inputs for independent torque/speed control
• AC Synchronous	Input voltage	Input frequency	External electronic switch (same as AC Induction)
• Switched Reluctance	Input voltage	Field rotation speed	External electronic switch (same as AC Induction)

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If we want to control both torque and speed independently, The classical DC motors are not really adequate. We only have control of the input voltage, and we get a constant power output for a constant input. The product of torque (load) and speed is a constant for constant inputs. If we increase the load, the speed decreases. The control seems simple. If we have a particular load, we just turn up the voltage until we get the speed we want. But speed or torque are never uniquely related to input.

At first, brushless DC motors had power processors which mimicked the classical DC characteristics, to reinforce the name "brushless DC". But if we have large motors (tens of horsepower), "turning up" DC sources that are 100's of volts and/or 100's of amperes is very undesirable. Therefore, switching regulator functions were incorporated into the control algorithms for the stator switches, and we gained the ability to independently control torque and speed through input voltage and frequency, respectively, with signal level inputs.

The power transferred to the induction motor rotor via transformer action is controlled by both input voltage and the transformation frequency (the slip frequency). For a fixed voltage, the slip changes to vary the output power and match the load. The difference in rotational speeds between the stator field and the rotor is often about 3% to 5%, so the typical slip frequency for a 400-Hz motor would be about 20-Hz.

The switched reluctance motor is not unlike a stepping motor with regard to its control. Windings distributed around the stator are alternately sequenced to produce a rotating field, which "pulls" the magnetic iron rotor along, trying to minimize the reluctance of the motor air gap. Like the classical brushless DC, the input voltage controls the air gap flux (field strength) and the frequency of rotation controls the speed.

Motor Selection Summary

- **Optimized motors from all the candidate classes have about the same mass and volume for the same requirements** (peak outputs are in the 3-HP/lb. range)
- **Basic control parameters are similar for all the candidate classes** (motors are multi-phase and we must have independent control of input voltage and frequency)
- **Feedback for torque and speed control is simplified for induction motors** (speed feedback vs. accurate rotor position for other types)
- **Modern control algorithms give induction motors dynamic advantages for servo systems** ("field oriented control" provides optimum response)
- **Induction or switched-reluctance motors significantly simplify the mechanical designs of redundant systems** (eliminate the requirement to decouple an inactive/failed motor)

General Dynamics is focussing on induction motors for ELA/ EMA development and implementation

The choice of "best" motor for high-power TVC applications cannot be made using the usual trade study approach, since all the usual trade parameters (mass, volume, cost, etc.) are close enough to each other for the primary candidates to make them non-discriminators. Even if they were significantly different, the are small compared to the rest of an EMA TVC system, and do not significantly influence system technology choice. The control algorithms and the design of the power output stage are also about the same for all three types. Even the somewhat easier feedback handling for the induction motor is still not enough to make it an obvious choice. So other considerations lead us to choices for specific applications or power ranges.

The "slip" power transfer relationship makes the induction motor significantly more robust in terms of load changes. For example, when our optimized Sunstrand induction motor is operating at full speed and its most efficient operating point, it has about 2% slip (14, 700 RPM). If its load were doubled, the slip would increase to about 4% to transfer additional output power and the speed would decrease to only 14,400 RPM. A permanent magnet Brushless DC assembly under the same conditions would decrease its speed from 15,000 RPM to 7,500 RPM (half speed), and the switched reluctance motor would stall; until the controller could increase the input to match the new load.

The biggest discriminator has to do with redundant systems, where multiple motors are used to drive a load. If there is a short circuit failure in a motor or its controller, the fixed magnetic field in the permanent magnet rotor makes that motor type function as a generator, supplying power to the fault, and loading the system. If the system is to work properly after one such failure, the remaining motor(s) must provide enough excess power to both drive the real load and the fault load, or the faulted unit must be mechanically decoupled. This added complexity is sufficient to disqualify permanent magnet motors (in the brushless DC design) from use in redundant systems.

Controller Operational Definition

The controller/power processor must provide the following primary functions:

- **Synthesize a multi-phase AC waveform appropriate to running several AC motor types**

  ("There is no such thing as a DC Motor")
- **Provide variable frequency for speed control**
- **Provide independent variable voltage/current for output torque control**

In TVC applications, it must also:

- **Provide closed-loop output position control in response to guidance steering commands**

The power processing and control block provides all the above functions. The power processing/inversion function is obvious if we have AC motors and DC power sources. But in addition to that interface function, we must also control speed and output torque. We have already discussed the desirability of independent control of those quantities.

In addition, typical TVC control loops provide provide engine position control for the outermost loop, in response to steering signals from the guidance and vehicle control function. Good system design demands that we add the additional position control functions into the controller, providing a variable rate/position loop, with rate proportional to position error.

Because of high output powers, high efficiencies and low losses are important to the problem of thermal control in flight.

Power Processor / Controller Selection Summary

- **Resonant power processing technology, with pulse-population control, is the only choice for high power systems**
  - Highest efficiency / lowest losses -
    Minimize power source requirements
    Simplify thermal control
  - Natural commutation minimizes power semiconductor stresses, and maximizes reliability and robustness
  - Controlled, single-frequency sine wave power minimizes EMI and noise
  - Designs are available for both AC and DC power sources and distribution systems
- **Resonant power processing technology is applicable to synthesize the required waveforms for all candidate motor types**

General Dynamics is focussing on resonant power processors/ motor controllers for EHA/EMA development and implementation

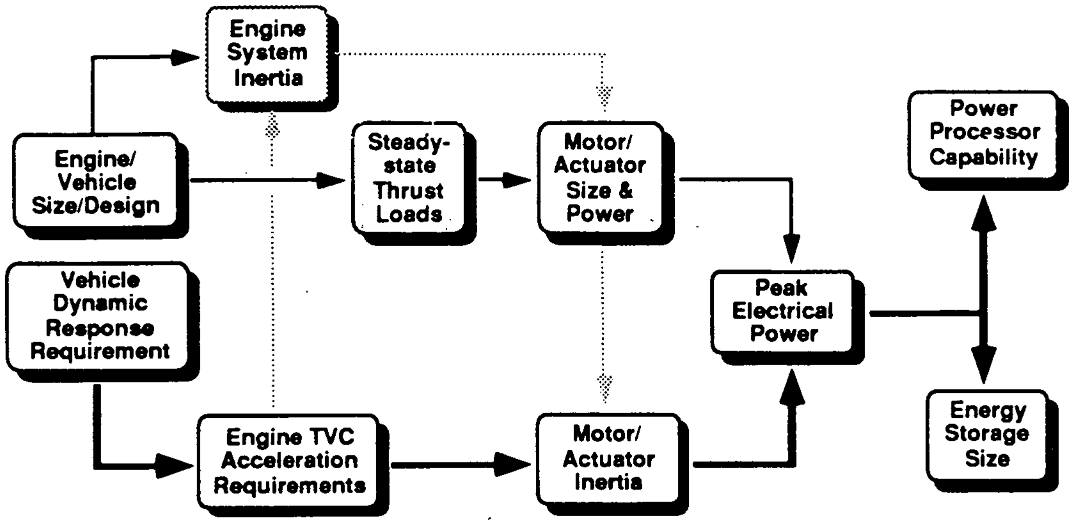
Resonant power processing has so many advantages, that it would be hard not to select it for high-power applications. The only "con" is the fact that it has not been widely used in our industry, and designers are not as familiar with the technology. For low power applications of motor control (in the limits of much of our present experience) the issue does not have much effect on overall system performance. We can easily remove the heat from a small amount of extra power lost to efficiency, and the effect on energy sources can also be small. A little bit of added high-frequency noise can be filtered, also with little overall system impact.

But these "annoyances" in small systems become major problems in large ones. Going from 10% losses to 5% losses in a 50-KW/50-HP system eliminates 2500-watts that the batteries don't have to supply and the thermal control system doesn't have to accommodate. Clearly, these considerations are no longer negligible for a launch vehicle or aircraft.

Since the two primary motor controller implementations (*switched-mode* and *resonant* power processing) both synthesize low-frequency motor currents, they may be selected on their own merits, and not impact the motor interface. Resonant power processing is the obvious choice, for the reasons shown above.

The most important factor influencing EMA TVC design is Motor and Actuator Inertia

Design Driver Flow



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This flow diagram is designed to show the interrelationships between the various elements from which EMA TVC requirements are derived; and the constrained end product of an EMA implementation.

At the far right are the output products which have the strongest constraints. They are discussed in more detail on Page 12. However, it is obvious that we would like to control the rest of the system to minimize peak power requirements.

On the vehicle requirements side, payload, environment, physical mass and volume, and dynamic response are the base sources for the actuator size and power requirements. But it's the mass acceleration side of the path that has the biggest impact.

For most actuator designs, the large effective gear reduction involved will make the effect of accelerating the engine system mass small when compared to the moments of inertia in the motor rotor and the actuator. About the best we can do is make the vehicle total load and the motor/actuator inertia effects about equal. And if we don't optimize the motor and actuator from a moment of inertia point-of-view, we can easily find an EMA for a 25-horsepower vehicle requirement requiring a 100-horsepower equivalent power input.

Since they are so highly-leveraged, it is fortunate that we have full control over motor and actuator moments of inertia and matching. But also, since they are so highly-leveraged, they are the elements with which we must take the most care, when we design them.

Primary Design Drivers

- **Acceleration of system inertias drives peak power requirements**
  - Step function response and bandwidth size transient drive torque capability
  - Input power is proportional to drive torque
- **Motor and gear train inertia have the greatest effect on peak power requirements**
  - Maximum efficiency for power transfer dictates equal power allocations for the load and the inertia
  - Load inertias are small contributors, when reflected to the input through the mechanical advantage of the gear train
  - Maximum efficiency for power transfer dictates equal inertias for the motor and gear train
- **Non-optimum designs can have peak powers that are four times the steady-state power**

Physical vehicle component parameters and vehicle dynamics are the base sources for the TVC system requirements. Thrust loads, gimbal bearing friction, feed system constraints, etc. determine the steady-state loads against which the actuator must push or pull. When we add the inertia of the movable masses in the engine system, and how fast we must accelerate them, we can size the actuator and its performance. For example, on NLS, the worst case generates a requirement for a 32,000-lb linear thrust and 32-horsepower if the rates are included. Motor and actuator steady-state mechanical losses are comparatively small (probably less than 5%).

But if we consider the power to accelerate the actuator masses and the motor rotor, we find that its difficult to get them down to 32-horsepower. And if we were to use conventional aerospace PM motor designs, it would not be unusual to get the acceleration power requirement to 100-horsepower by itself; making the total peak input exceed 130-horsepower, for a 32-horsepower system.

Primary Design Limitation Factors

- **Even with modern power processing technology and components, systems are primarily limited by "flyable" power processing capability**
  - Component limitations
  - Thermal control capability
- **Energy storage elements for these applications are primarily sized by peak power demands**
  - Battery size or rotating machinery drive components both impact vehicle design
- **Motor input power capability limits frequency response and step response**

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Power processing capability is limited by the capability of the flight-capable technology currently available in our industry. Signal processing and control capability is more than adequate. But if we look toward power processing components, IGBT's are the most promising, and even they are at their best in the newer resonant circuit topologies. While larger units and parallel controllers are possible, practical equipment design considerations push us toward trying to keep system peak powers below 100-horsepower.

When the energy storage requirements get large (to provide very high peak powers), the mass and volume of batteries get large enough to impact vehicle design. If we choose turbine-driven alternators for greater physical efficiency, the fluid systems to run them add complexity, impact propulsion system design, and compromise operability.

Finally, since input power capability limits torque and actuator acceleration, frequency response and step response are also limited. While our vehicle dynamics analyses have shown that an NLS-type vehicle only requires a 2-Hz system response (and that is no problem), higher bandwidth systems will allow us to have active control of stiffness and damping, to control vehicle high frequency effects.

The bottom line says the we would like to design EMA TVC hardware with low transient power requirements.

Summary

- **Resonant power processors / motor controllers are the best choice for high-power ELA/EMA's with both DC and AC sources**
- **Induction motors are best for redundant, high-power, TVC assemblies**
- **Power capability is the limiting factor in ELA/EMA performance**
  - Step response
  - Frequency response and bandwidth
- **Motor/actuator inertia is the single most important (and often neglected) mechanical design parameter for integrated high-power TVC systems**

Notes:

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- **"Electromechanical Actuators for Aerospace Vehicles"**; Jim Mildice, General Dynamics - Space Systems Division; presentation at MSFC, August, 1991
- **"25-HP Inverter/Controller/Motor"**; Jim Mildice, General Dynamics - Space Systems Division; Electromechanical Actuators, ALDP Avionics Area Review, December, 1990
- **"AC Bidirectional Motor Controller"**; Ken Schreiner, General Dynamics - Space Systems Division; December, 1990

EHA System Design Methodology

NASA Electrical Actuation Technology Bridging Workshop @ MSFC

9/29/92

John Anderson
(206) 773-0188

BOEING

Power Switching "Enabling Technology"

High power devices

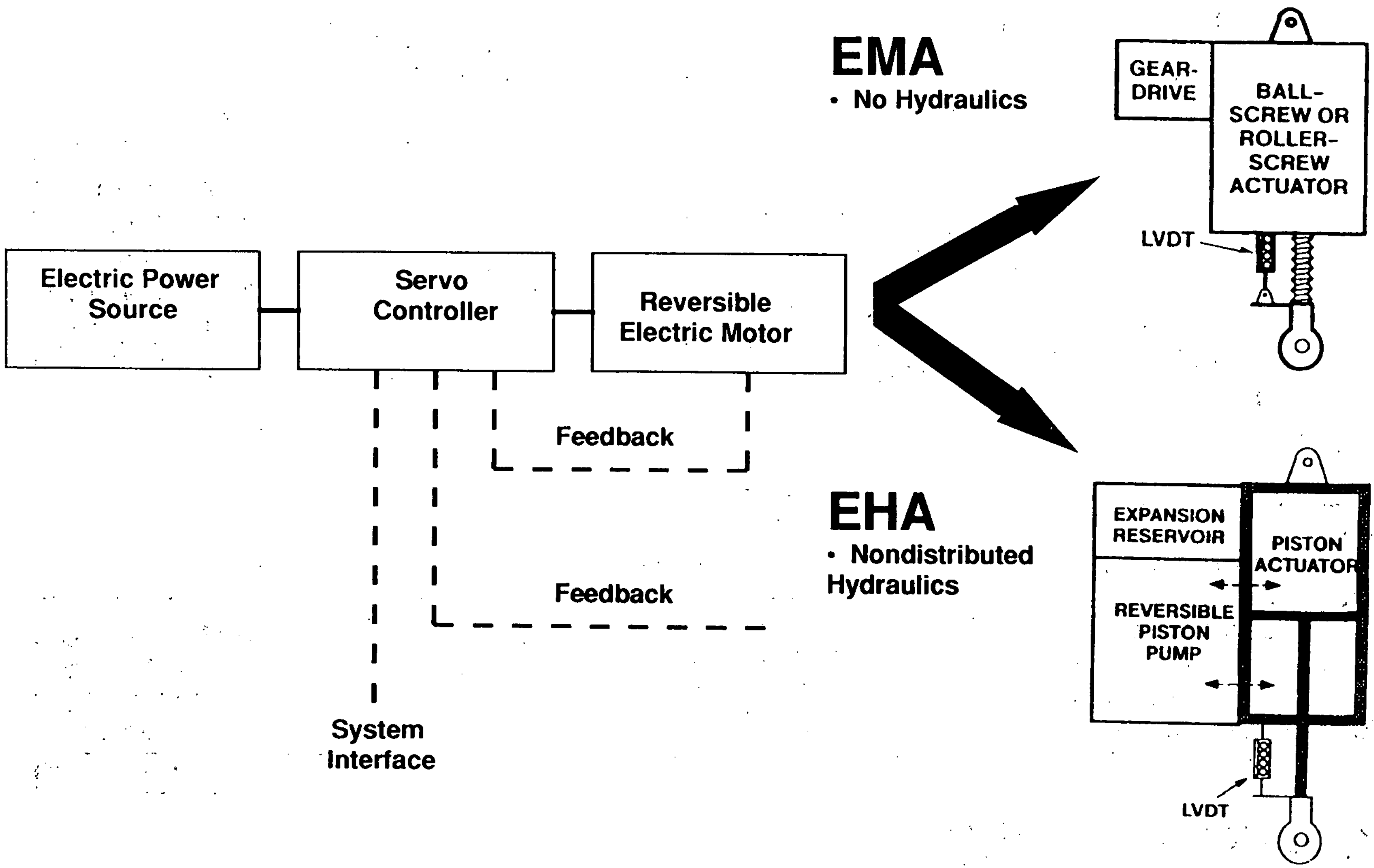
Bi-Polar /FET hybrids available 1990
50-100 amp, 600volt

IGBT developed/in testing, available 1992
100-400 amp, 120 volt
high voltage/small size

MCT in development, available 1997
100-300 amp, 1200 volt
high temp/small size

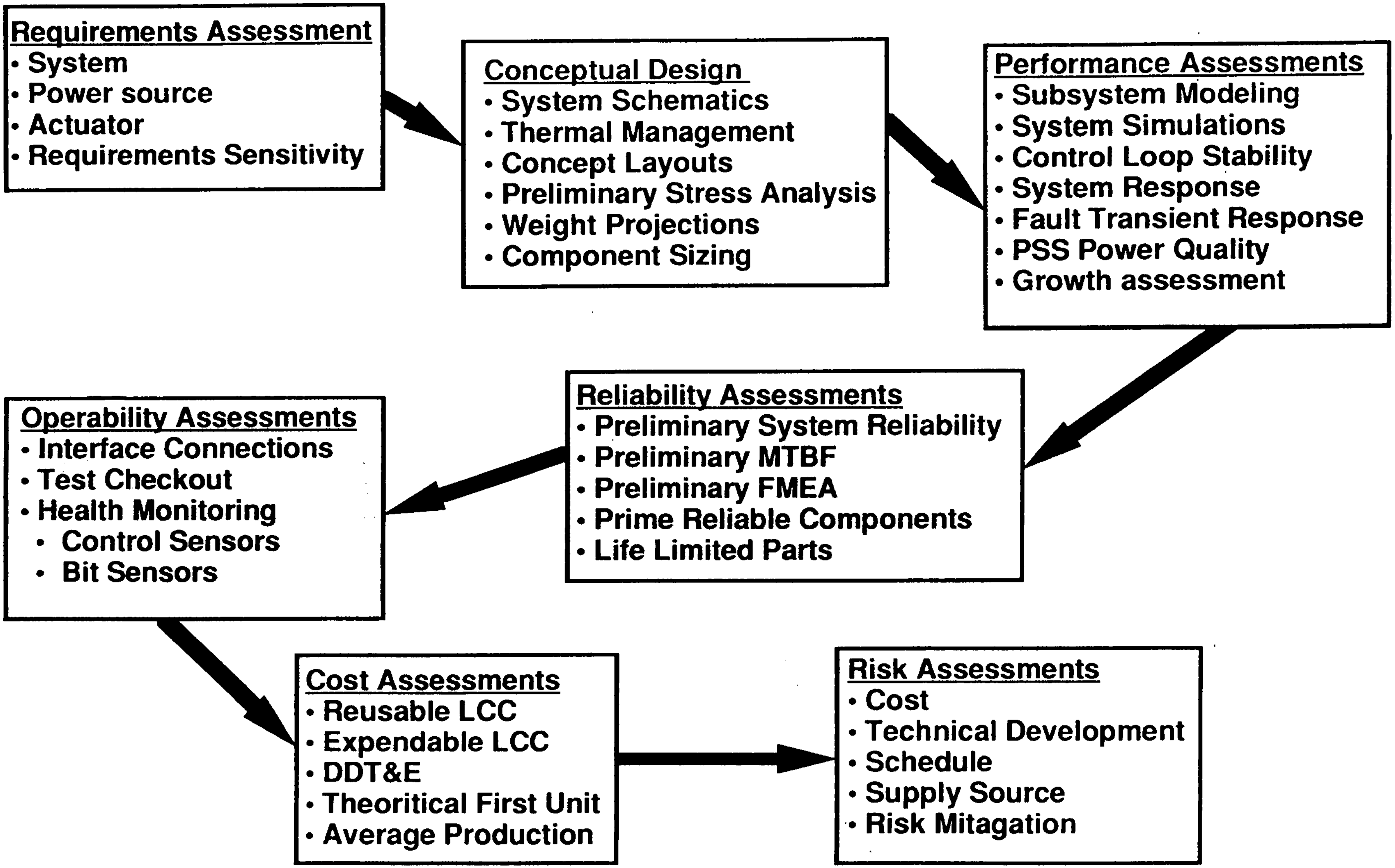
BOEING

Electric Actuation (ELA) Options



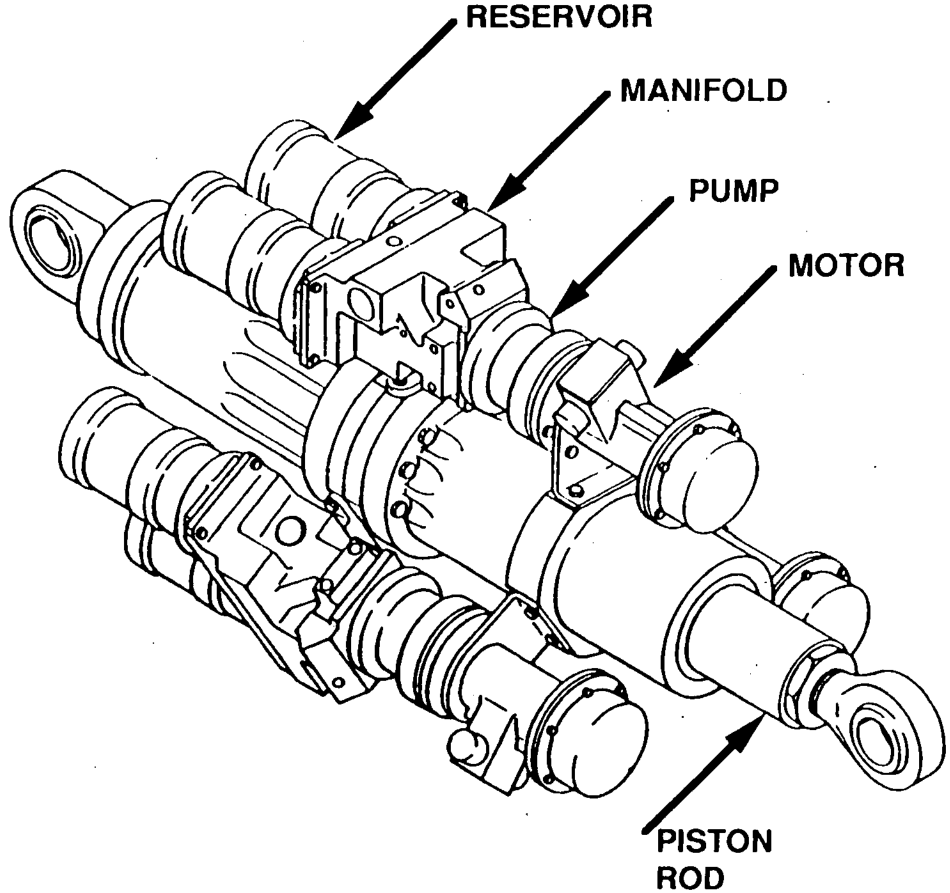
BOEING

EMA/EHA Design Methodology

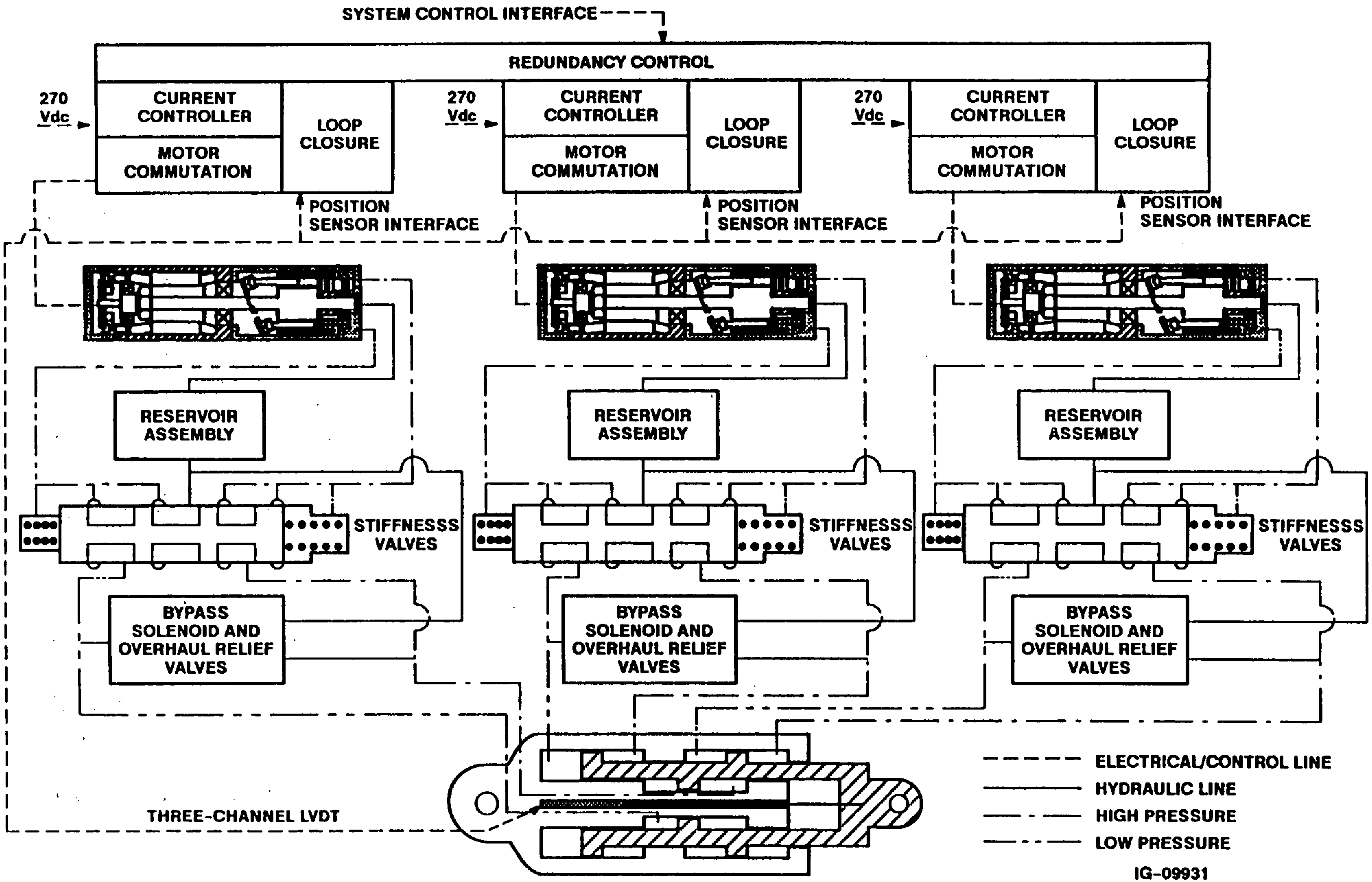


EHA Selection

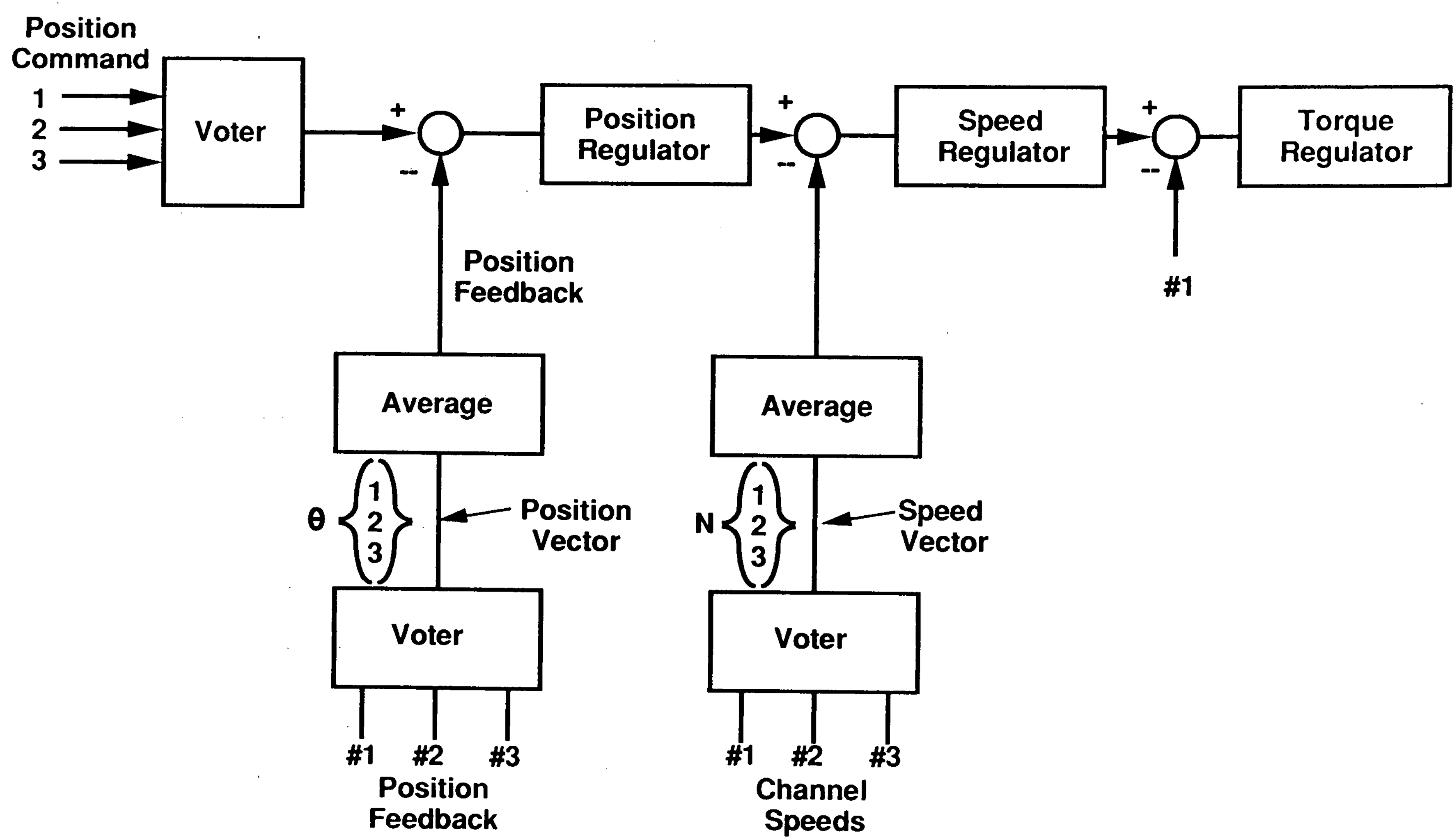
- No single point failures
  - Non-jamming piston/cylinder
- Fault tolerant redundancy management
  - Relief valve channel disengagement
- Transient Load Relief
  - Relief valve instantaneous response
- Thermal Management
  - Fluid immersed motor
- Self contained Hydraulics
  - no hydraulic lines/fittings
  - proven rod seal design
  - limited fluid volume
- Inherent Damping
- Zero Backlash



EHA Block Diagram



EHA Controller Schematic



Brushless DC Motor/PWM Control Selection

Permanent Magnet Motor Selection

- Options: Permanent Magnet Motor, Induction Motor, Switched Reluctance
- PM lowest inertia/highest torque/best dynamic response
  - Highest effeciency
  - Highest reliability
  - Excellent thermal capacity (low rotor losses)

Digital PWM Control Methodology Selection

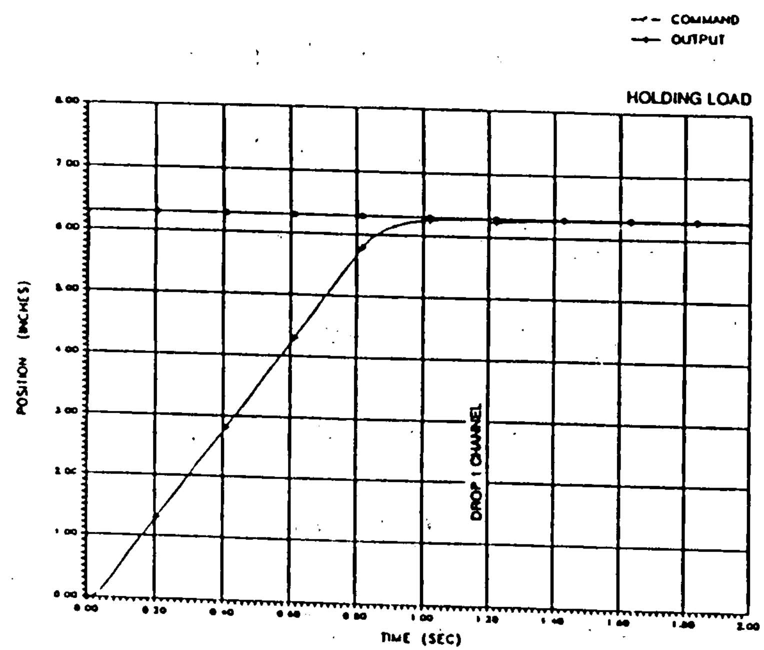
- High power density
- PDM in R&D stage/no payoff for this application

Application of Existing Technologies

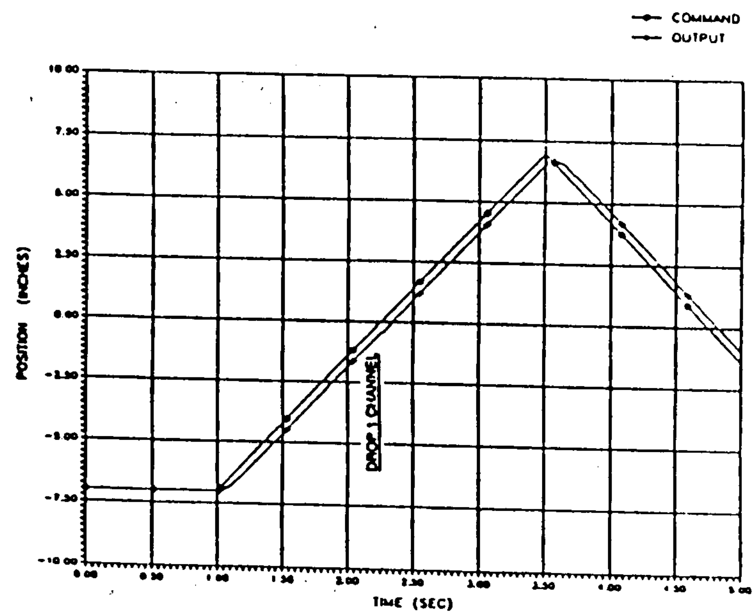
- Commercial Aircraft
- Space
- Military qualified hardware exists
  - J-STARS 15 hp redundant antenna drive
  - Flown in "Desert Storm"

EHA Redundancy Management

EHA Load-Sharing Simulator Failure



Holding Load



During Slew

Electric Actuation Drivers

- Power Switching Technology
- Technology Maturity
- Operability (Test, Checkout, Maintenance)
- Reliability
- Fault Tolerance
- Channel Load Sharing
- Redundancy Management
- Thermal Management/Regenerative Energy
- Transient Load Relief
- Packaging/Sizing
- Voltage Level
- Performance (Frequency Response, Load/Stroke, Duty Cycle)

BOEING

UNIVERSITY OF ALABAMA IN HUNTSVILLE

ELECTROMECHANICAL ACTUATOR

AND

MOTOR OPTIMIZATION

TASKS

PRESENTED TO THE

ELA TECHNOLOGY BRIDGING PROJECT WORKSHOP

by

GEORGE B. DOANE III

HUNTSVILLE AL SEPTEMBER 1992

TASK ONE

Examine EMA-TVC Subsystem Specifications

Prove Feasibility of EMA/TVC Subsystem By Means of a Point Design Meeting NLS/SSME Requirements

Demonstrate Point Design Characteristics by Simulation

Drive Out Potential Problem Areas

Establish Critical Component Specifications

Subsystem Specifications

The static and dynamic specifications applicable to the EMA as applied to the NLS are mostly yet to be determined on a definitive basis. However, it is known that many of the physical parameters of the new engine will be close to those of the current SSME. The structure to which the engines will be attached is likewise undetermined at this time. However, past experience with a number of launch vehicles suggests that at least as far as natural frequencies of the structure are concerned current SSME values are typical. Assuming they are within a representative range it will not be too difficult to tune the designs arising from present knowledge to accommodate the eventual actual values.

Following SSME practice leads to a stall force requirement as well as a horsepower rating. It has been customary in the past to rate hydraulic actuators in terms of horsepower even though they are used over a range of speeds i.e. around zero to plus and minus maximum velocity values. In the current design this power is to be reached at 5 in/sec actuator stroking velocity. It is more informative to examine torque speed curves over the whole operating envelope. This is particularly true when dealing with electric motors as the actuating component because they are capable of delivering much power or torque in off nominal conditions (provided the situation requiring much current does not last too long).

The number of motors and their horsepower rating was suggested by MSFC and may implement various redundancy schemes.

Three charts drawn directly from Rockwell documents specifying the SSME actuation system frequency and transient allowable envelopes are shown.

Examine EMA-TVC Subsystem Specifications

Stall Loads Specified by MSFC (60 Kips)

Three Motor Configuration Specified by MSFC

Each Motor to Produce 10 Horsepower at 5 in/sec Actuator Stroking Velocity

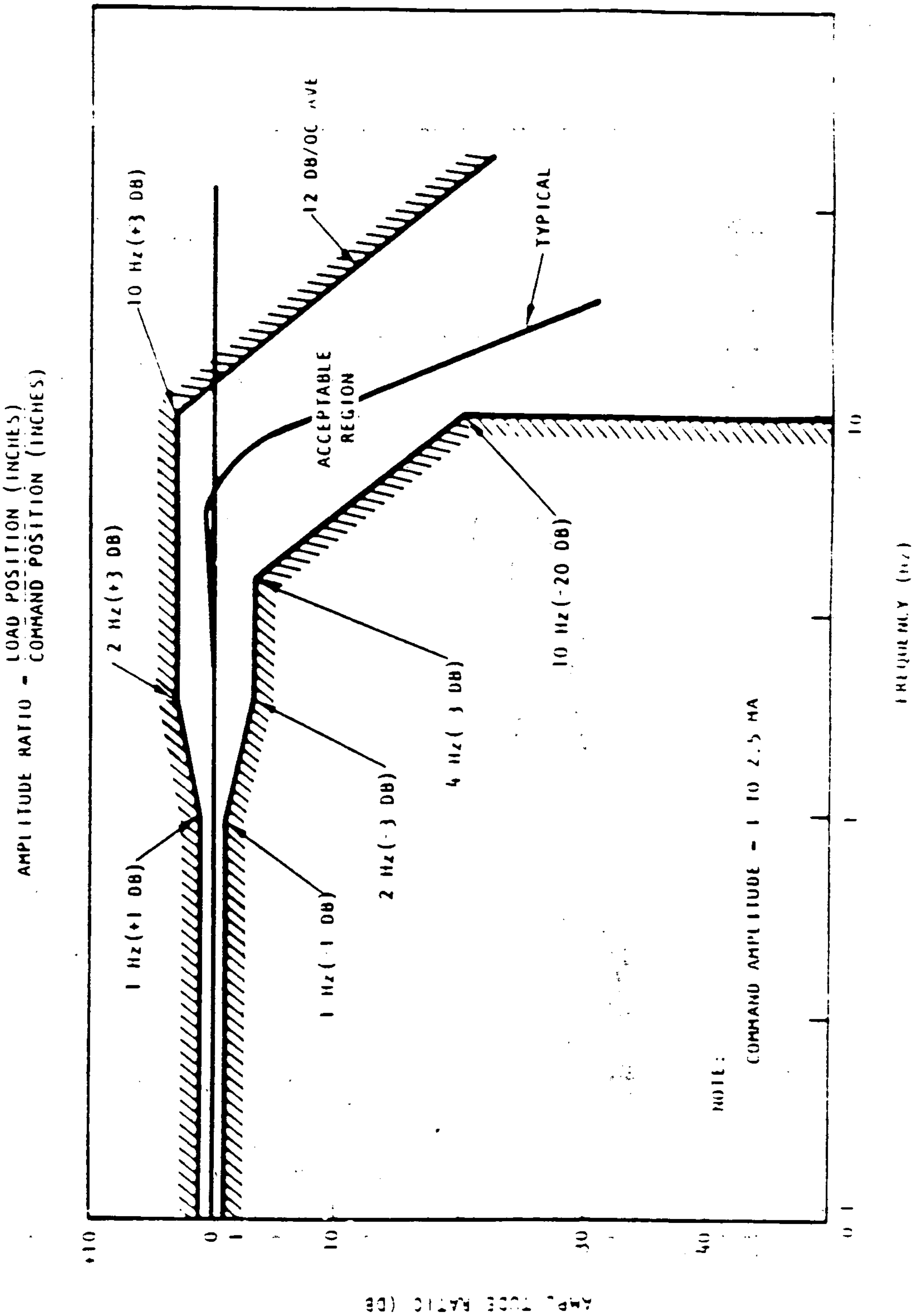
Each Motor to be Capable of 15 Horsepower at 5 in/sec

Maximize Power to Load During Accelerated Motion

Posses Robust Recovery From Saturated State

- Frequency Domain Specifications
- SSME Document
- Flight Dynamics Requirement

Time Domain Specifications
- SSME Document
  - Large and Small Amplitude


AMPLITUDE RATIO = LOAD POSITION (INCHES) / COMMAND POSITION (INCHES)
12 DB/OCTAVE
10 Hz (+3 DB)
TYPICAL
ACCEPTABLE REGION
2 Hz (+3 DB)
10 Hz (-20 DB)
4 Hz (-3 DB)
2 Hz (-3 DB)
1 Hz (+1 DB)
1 Hz (-1 DB)
NOTE:
COMMAND AMPLITUDE - 1 TO 2.5 MA
FREQUENCY (Hz)
+10
0
10
30
40
1
10
AMPLITUDE RATIO (DB)

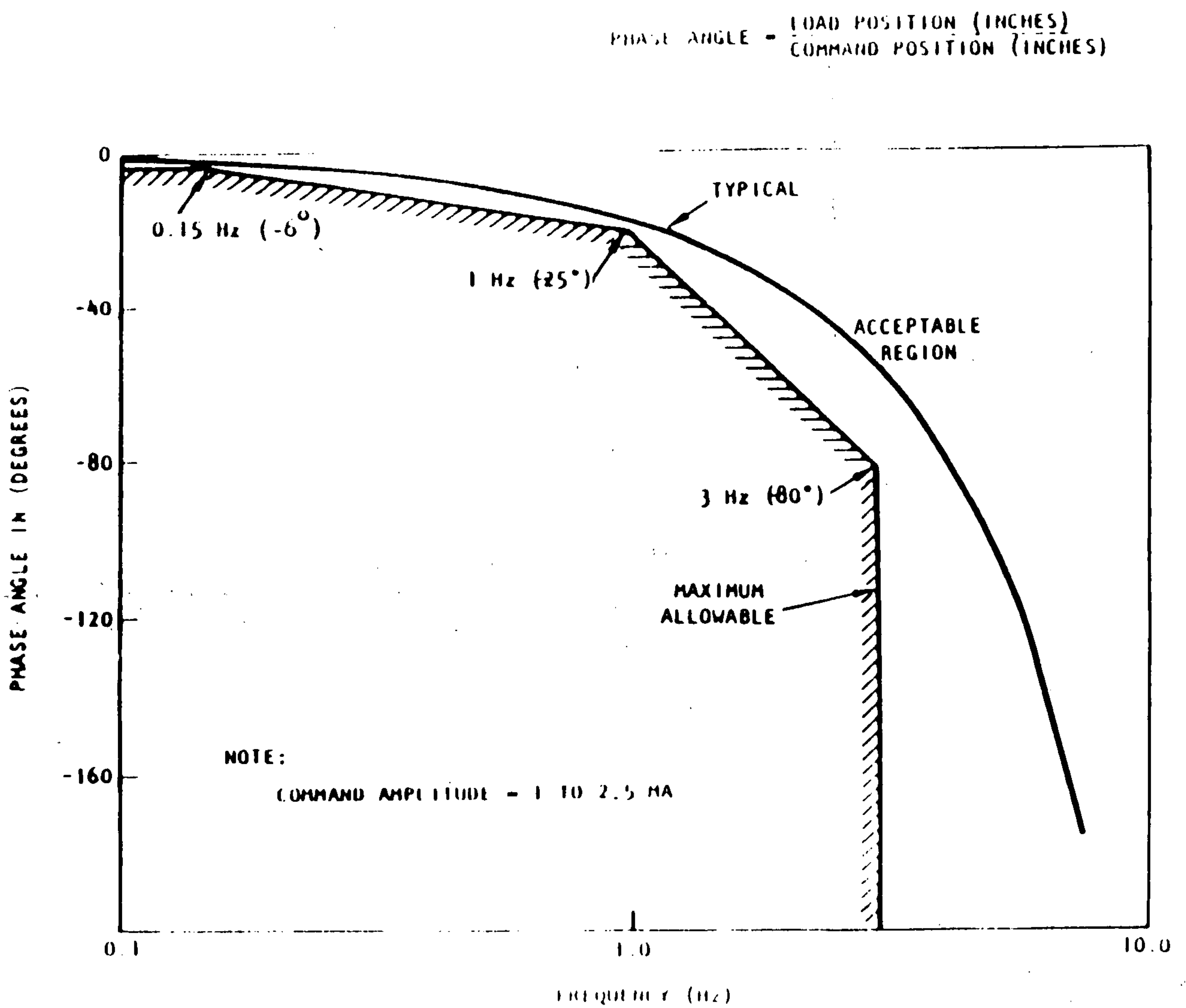
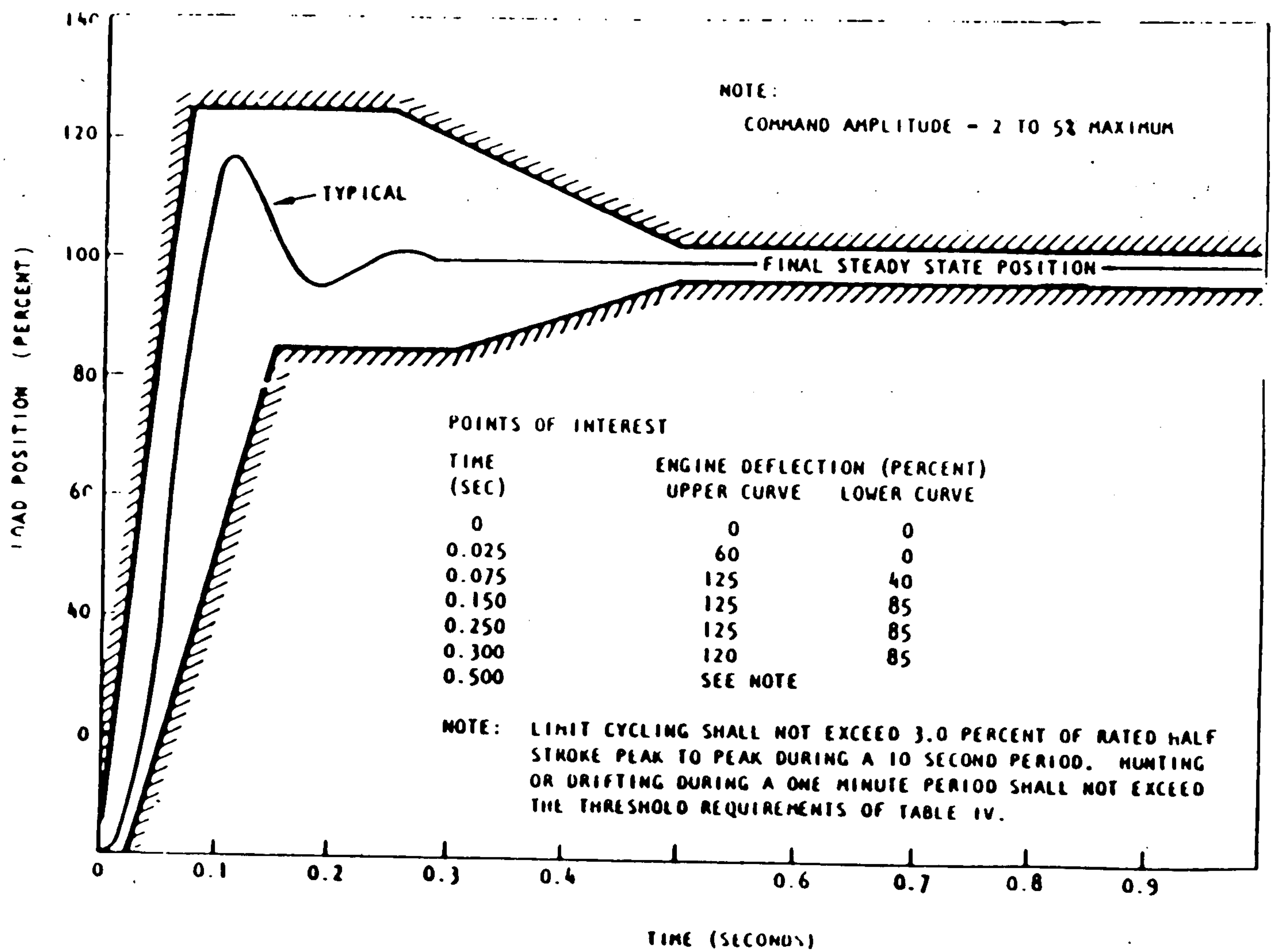


Figure 16 — Frequency Response Phase Requirements


NOTE:
COMMAND AMPLITUDE - 2 TO 5% MAXIMUM
TYPICAL
FINAL STEADY STATE POSITION
POINTS OF INTEREST
TIME (SEC)
ENGINE DEFLECTION (PERCENT)
UPPER CURVE
LOWER CURVE
0 0 0
0.025 60 0
0.075 125 40
0.150 125 85
0.250 125 85
0.300 120 85
0.500 SEE NOTE
NOTE: LIMIT CYCLING SHALL NOT EXCEED 3.0 PERCENT OF RATED HALF STROKE PEAK TO PEAK DURING A 10 SECOND PERIOD. HUNTING OR DRIFTING DURING A ONE MINUTE PERIOD SHALL NOT EXCEED THE THRESHOLD REQUIREMENTS OF TABLE IV.
LOAD POSITION (PERCENT)
140
120
100
80
60
40
0
0.1
0.2
0.3
0.4
0.6
0.7
0.8
0.9
TIME (SECONDS)

NLS Derived Specifications

Preliminary work accomplished by the MSFC flight dynamics personnel working in the flight control area produced some preliminary equivalent system small angle response specifications in the frequency domain. While the point design meets these specifications they are included here for completeness sake.

Small Angle Time Domain Specifications From Flight Mechanics

Second Order System

Bandwidth..4.2 Hz

Damping Ratio....................................0.7 of Critical

TVC Commands In Range of.................................0.25 Degree

Specifications Above Translate Into

Minimum Gimbal Velocity....................4.7 deg/sec

Minimum Gimbal Acceleration........120 deg/sec/sec

DESIGN APPROACH

The mechanical layout used in this study was suggested by various in-house designs extant at MSFC. MSFC also suggested that a range of the roller screw ratio not to exceed one inch per revolution and a spur gear step down ratio not to exceed ten were appropriate.

Because of a desire to minimize the electric current from the supply when accelerating the load, the technique of matching the actuator mechanical impedance to the load mechanical impedance was adopted. A fortuitous byproduct of this approach turned out to be that it yielded, when properly formulated, a unique solution for the two reduction ratios (rather than for the ratio of the two as other formulations do). Of course it was still necessary to produce specified stall torque which in turn was not necessarily compatible with he impedance matching criteria. This effect was investigated for a range of available motors producing the specified horsepower at different speeds. It was found that a relatively more massive motor turning at slower speed minimized the "detuning" from the matched impedance case necessary to meet the required stall force condition. From this investigation a motor specification for speed and inertia was developed.

At this early stage of investigation the nonlinearities considered were the torque saturation of the motor and the stroke constraint of +-5 inches. Friction was assumed zero or nearly so and gear backlash was not modeled. Modeling this latter phenomenon awaits laboratory experiment because various anti backlash measures were either being incorporated or contemplated at the time of this design work.

To demonstrate that it is feasible to substitute this type of actuator for the previously used hydraulic one the design used the specifications previously applied to hydraulic actuator designs for the SSME and also followed the well verified design methods of the hydraulic actuators i.e. the type of feedback and the design methods used. This approach proved to produce very acceptable results.

A good deal of digital simulation was used both during the design phase of the work and to verify the designs in off nominal operation. An example of the latter was to perform a check on the unloaded or "out of the box" stability of the actuator servo design.

Design Approach

Assume Use of Roller Screw With Maximum Lead of 1 Inch Per Revolution

Assume Use of One Spur Gear Pass

To Minimize Acceleration Power Use Mechanical Impedance Matching
Also Maximizes LOAD Acceleration (Hence Bandwidth)

Assume Major Nonlinearities Are Torque Saturation and Stroke Constraint
+,- 5 Inches

Generally Base Design On Previous Hydraulic Experience

Use OTT Servo Techniques (Frequency/NYQUIST and Root Locus)
No Conditional Stability Was Allowed For Any Configuration

Use Simulation Liberally to Aid In Design and to Verify Results

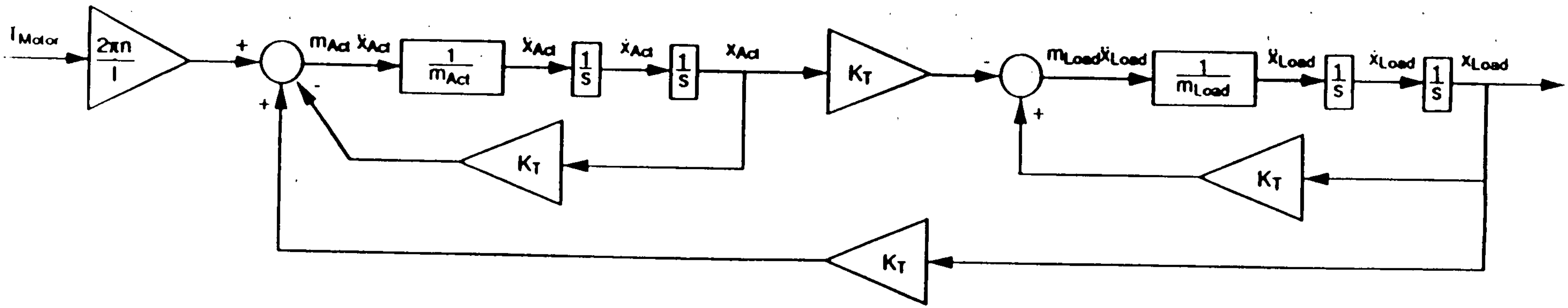
Modeling Notes

The equations of motion of the actuator system with its motor load were written assuming that the various constituent pieces behaved as a collection of springs and masses. The motor was modeled as a spring and a mass in series as was previous practice. The various springs were combined in series/parallel as appropriate and an equivalent spring derived and used in the model. In the process some very stiff springs became negligible in the model. This model is implemented in the 4656 "iron horse" simulators e.g. the 8 Hz mode. The resulting four state model was constructed so that the physical quantities were readily available. It will be noted that this form of a model makes the actuator and the engine (and their states) readily identifiable. Damping was neglected in the basic model (and was only used very sparingly when numerical problems in such things as frequency responses arose). The justification for this was that structural damping tends in practice to be quite small (0.5% of critical is often used) and that it probably would err on the side of stability conservatism. The drawback was that the simulated system tends to be a little faster in response than is found in the laboratory where some friction is found.

Model Used

Four State Model

Mass of the Actuator
Mass of the Engine (Load)
Spring Constant Representing the Compliance of the
Engine and the Support Structure



Simulation Model Developed From The Equations Of Motion

Gearing Optimization

The gearing was optimized to produce impedance matching or, what is the same thing, maximum load acceleration. The method is straight forward and generally follows the seminal work by Petersen in the 1950s.The expression for the load acceleration is written and then maximized with respect to the available gear ratios. The key to obtaining a closed form, unique solution lies in assuming (as Petersen did) that the larger of the spur gears has an inertia equal to that of the smaller gear times the gear ratio raised to the fourth power. As is seen in the accompanying slides substitution of the proposed design's numerical parameters produces the desired answers. For this design it was shown that the dominating effects are the inertia of the motor and the inertia of the load and that other parameter changes produce negligible perturbations in the design. The details of the differentiations and the solution of the resulting algebraic equation were all carried out by a symbolic manipulation computer program.

Opimization of Gearing

Maximize Load Acceleration
Minimize Acceleration Power Requirement

These Produce The Same Result

Proceed By Maximizing The Load Acceleration
There is a Unique Closed Form Solution for the Spur gear and the Roller Screw Ratios IF One Assumes That the Inertia Of the Larger of the Spur Gears Is N^4 Times the Inertia of the Smaller Gear

An Example

Acceleration of the Load

$$\alpha_{Load} = \frac{\text{Torque}}{J_{3\text{-}Motor}[\frac{2\pi n}{l}] + [J_{Pinion\ Gear}(3+n^2)][\frac{2\pi n}{l}] + J_{Roller\ Screw}[\frac{2\pi}{nl}] + M_{Engine}[\frac{l}{2\pi n}]}$$

Mechanical Parameters

$$J_{3\text{-}Motor} = \frac{(3)(565)(15)^{3/2}}{(5)(3000)^{5/3}} = 0.0315598 \text{ in-lbs-sec}^2$$

$$J_{Pinion\ Gear} = 0.00004768 \text{ in-lbs-sec}^2$$

$$J_{Roller\ Screw} = 0.016 \text{ in-lbs-sec}^2$$

$$M_{Engine} = 55 \frac{\text{lbs}_f \text{ - sec}^2}{\text{in}}$$

Substituting to Obtain Denominator Expression

$$\alpha_{Load} = \frac{\text{Torque}}{[0.0315598][\frac{2\pi n}{l}] + [(0.00004768)(3+n^2)][\frac{2\pi n}{l}] + [0.016][\frac{2\pi}{nl}] + [55][\frac{l}{2\pi n}]}$$

Let Computer Take Derivatives of Denominator With respect to n and l

$$D1 = \frac{0.198296}{l} - \frac{0.100531}{l\,n^{2}} - \frac{8.75352\ l}{n^{2}} + \frac{0.000599165\ n^{2}}{l} + \frac{0.000299582\ (3. + n)^{2}}{l}$$

$$D2 = \frac{8.75352}{n} - \frac{0.100531}{l^{2}\,n} - \frac{0.198296\ n}{l^{2}} - \frac{0.000299582\ n\ (3. + n)^{2}}{l^{2}}$$

Set Equal to Zero and Let Machine Find Solutions for n and l

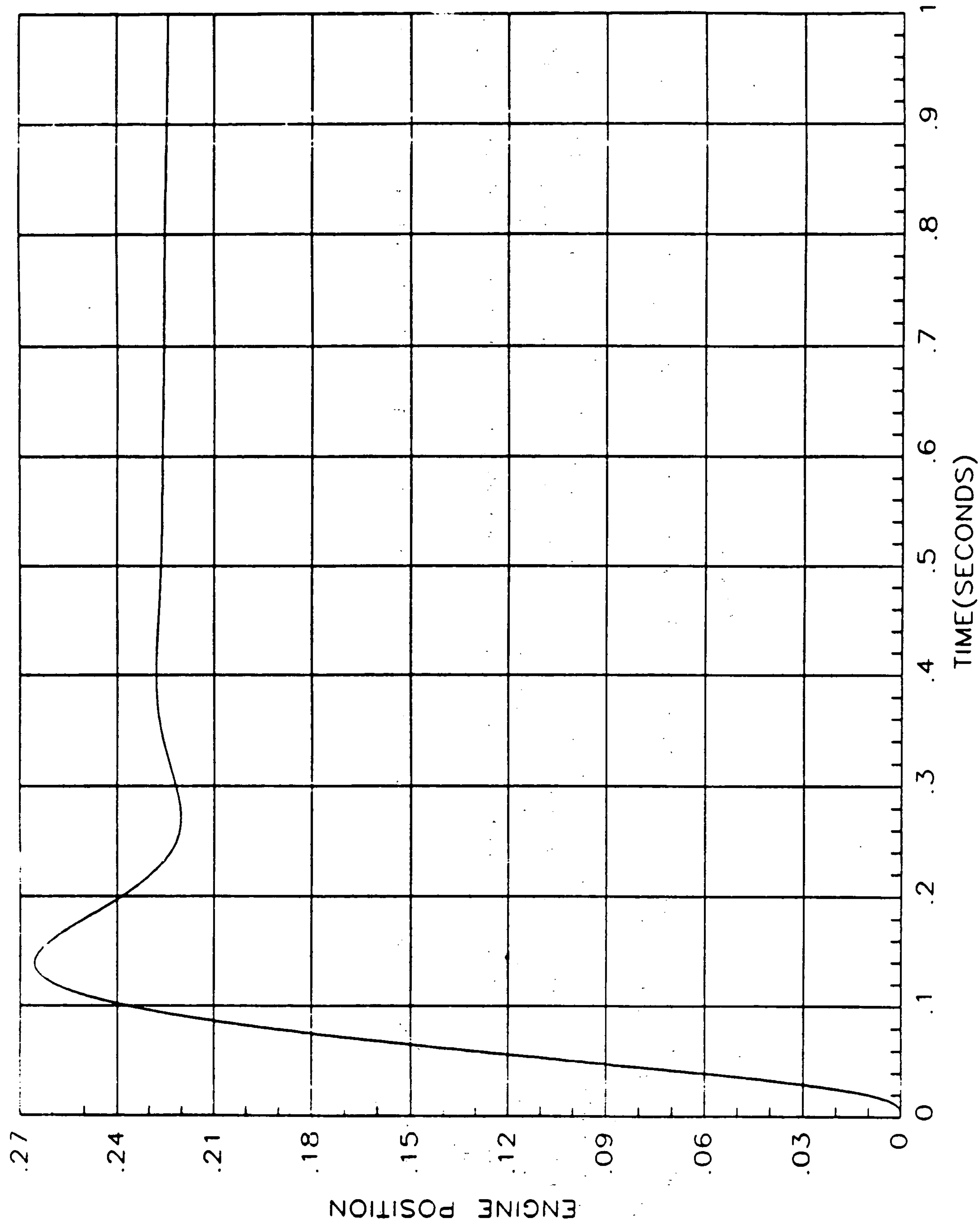
{l -> 0.663194, n -> 4.28002}

Servo Design

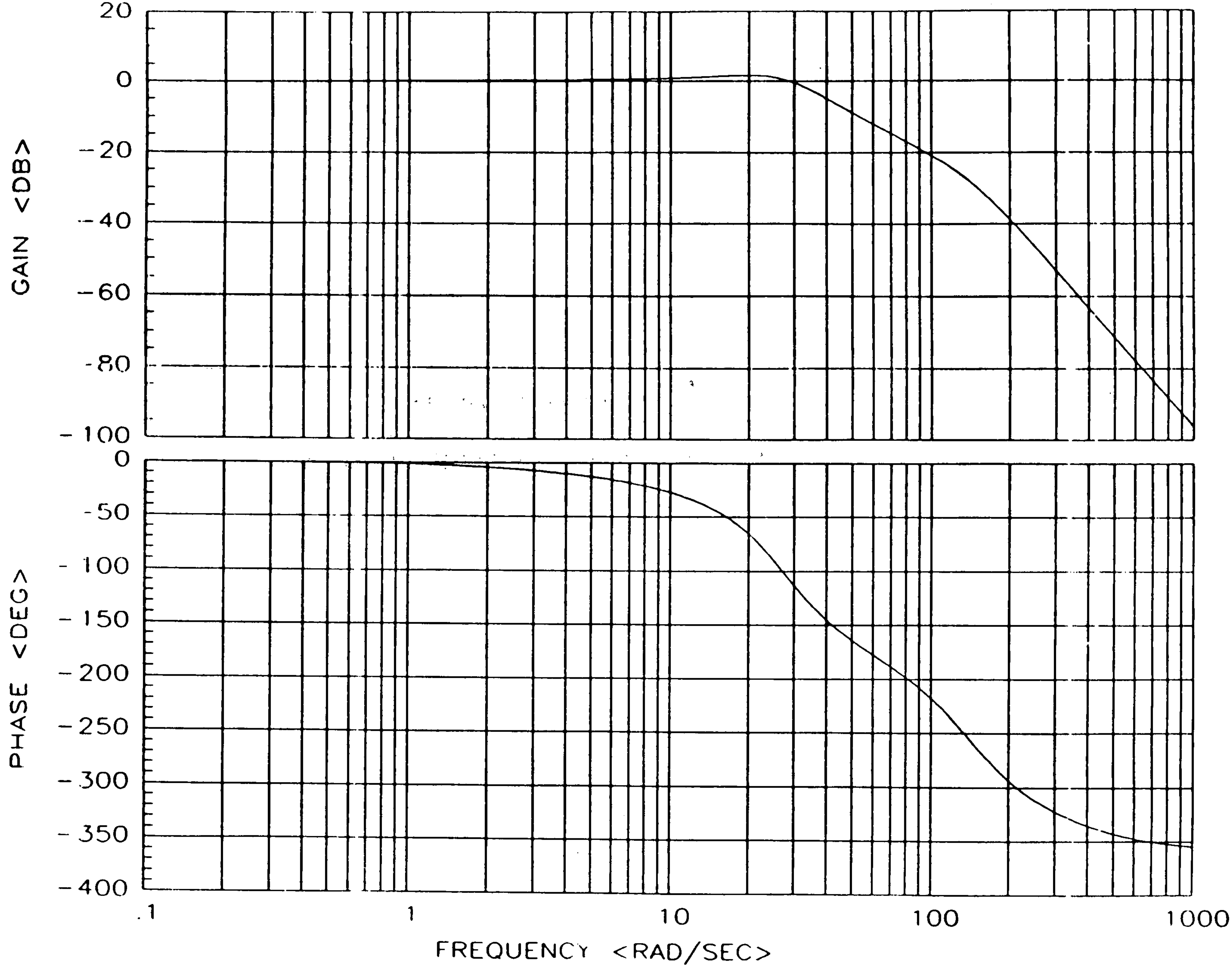
Earlier SSME servo design practice was followed. Note that states of the load are not measured although there are systems in existence which do so.

As previously mentioned classical techniques i.e. frequency response and root locus were used in the servo design process. The results were verified by extensive simulations with the aforementioned nonlinearities included. An effort was made to make the electronic or signal gain paths as low gain as possible. However, the desire for high system bandwidth resulted in higher than desired signal gain and therefore some attention to signal noise control will probably be necessary.

The resulting system's step and frequency responses are shown in two slides. It is seen that the system meets the linear specifications.



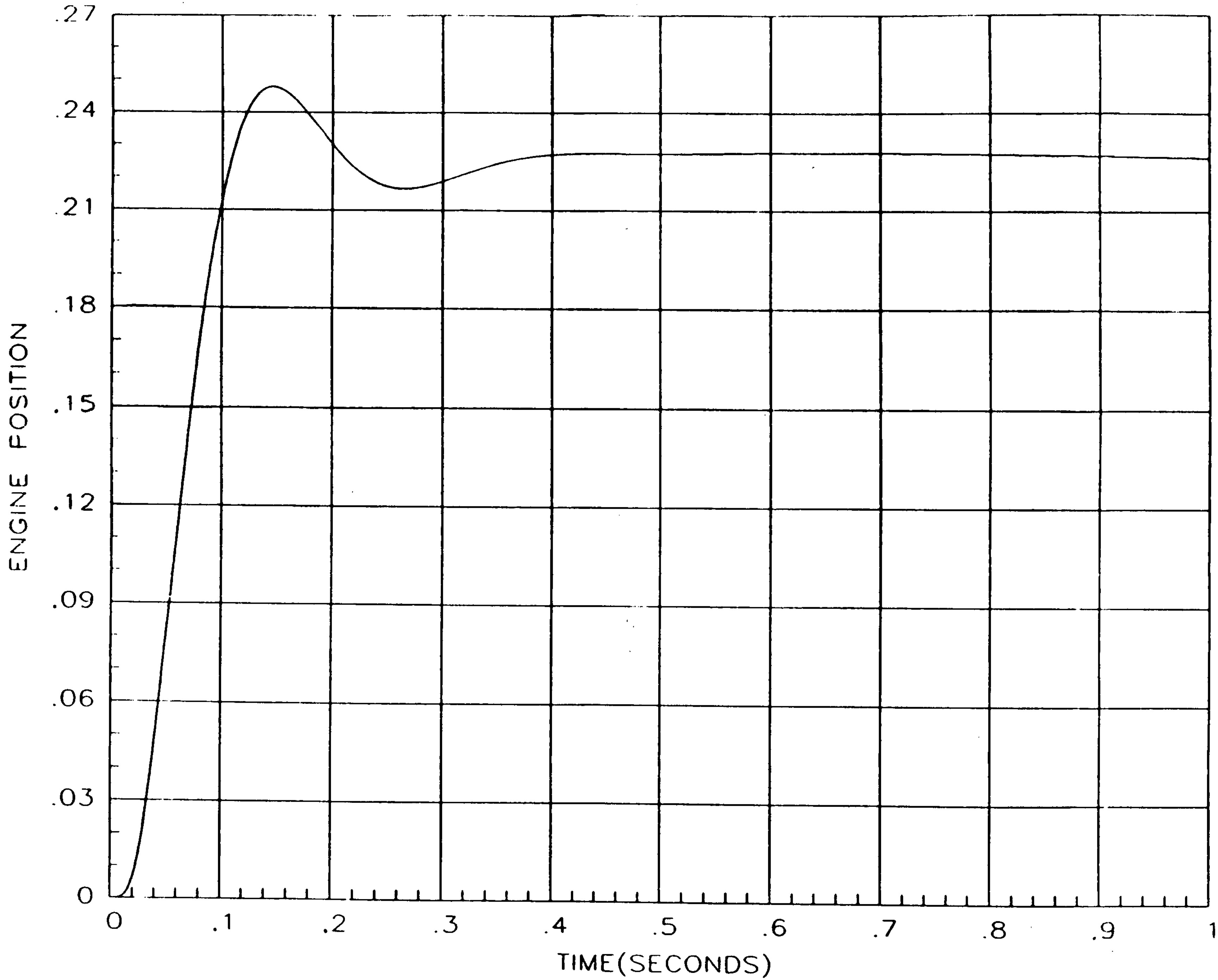
STEP CHANGE IN INPUT COMMAND AT 4% INPUT AMPLITUDE



GAIN <DB>
20
0
-20
-40
-60
-80
-100
PHASE <DEG>
0
-50
-100
-150
-200
-250
-300
-350
-400
.1
1
10
100
1000
FREQUENCY <RAD/SEC>

Saturation Nonlinearity Effects On Commanded Response

No Unexpected Happenings



STEP CHANGE IN INPUT COMMAND AT 4% INPUT AMPLITUDE

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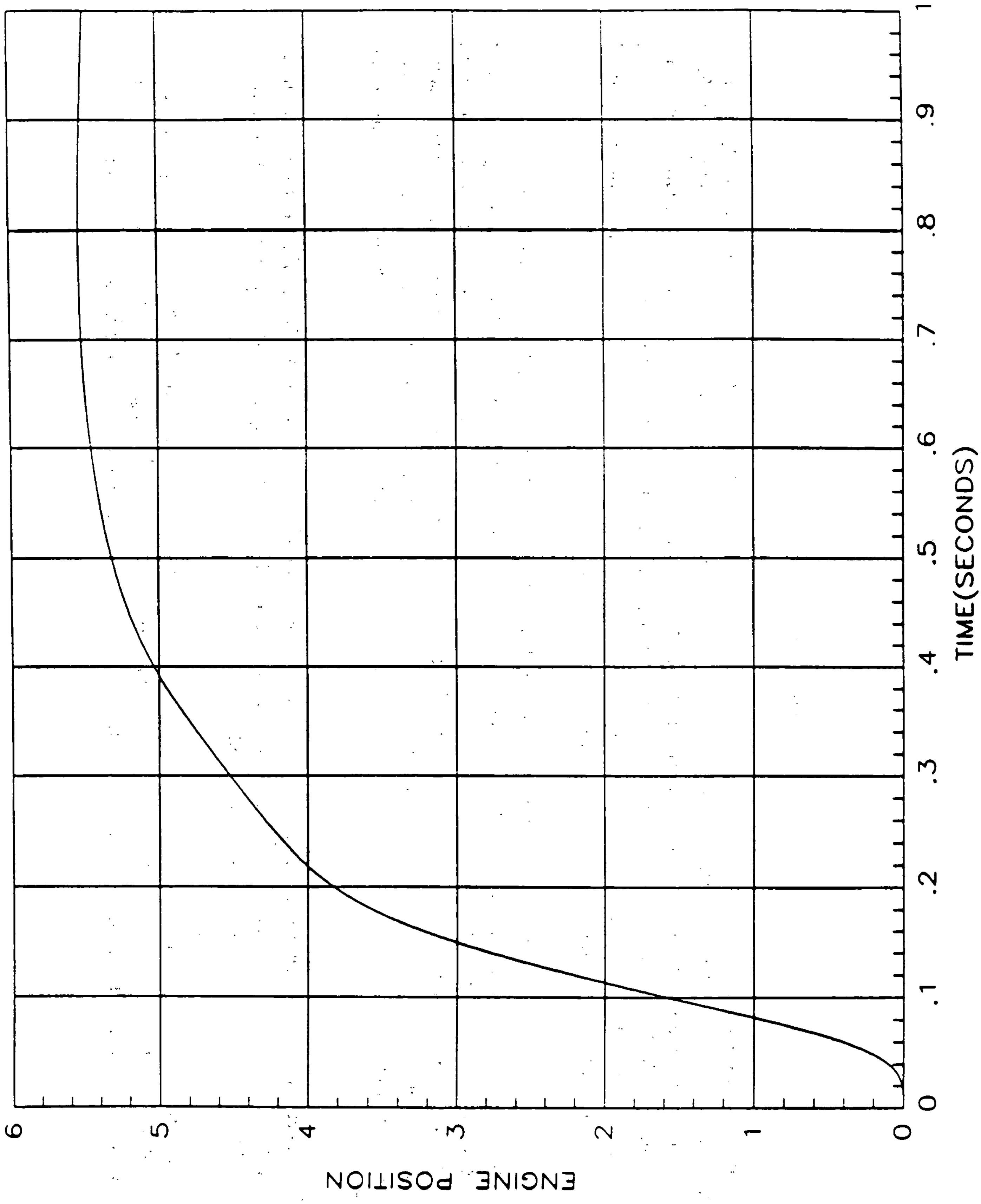


RESPONSE TO 5 INCH STEP COMMAND

Disturbance Response

It has proven impossible, at least for this author, to obtain accurate characterization of the engine start/stop transient forces as seen by the actuator. Inspection of raw force data obtained during firings of the MSFC Technology Test Bed, for example, reveals a highly oscillatory response of the strut force and the engine position. This is probably due to the fact that the so-called struts or stiff arms are anything but stiff. They are in reality a pre stressed spring made up of a series stack of Bellville like washers. Indeed a little reflection shows that the arms and hence the actuators when used must give or yield to relieve loads on the engine structure so as not to damage it.

Hydraulic actuators have very high output impedance to motion caused by forces applied to them. Pressure relief to limit loads may be incorporated in the form of pressure relief valves and so on but never the less they are relatively immune to start/stop transient caused motion. This is not inherently true of this form of electric actuator. The gearing used in them is of high efficiency and therefore may be back driven. This latter fact means that large amplitudes of motion are possible unless something is done to prevent them. Of course the amplitude of the motion is a direct function of the force applied by the start/stop transients depending upon magnitude, duration and one supposes on the particular function of the force versus time.

MSFC suggested that square shouldered pulses of 20, 40 and 60 kip amplitude and 400 milliseconds duration be investigated. This was done using the model developed from the servo design effort. At the 60 kip amplitude unacceptably large engine motion response occurred.

This result leads to the largest potential problem arising from the investigation. There are two approaches to understanding it better and coping with it. First some effort expended in investigating the start/stop transients is in order and second some overt response limiting measures should be undertaken. One simple scheme is explained later.

DISTURBANCE RESPONSES

Disturbance Pulse Charactization

Sharp Cornered Rectangular Pulses

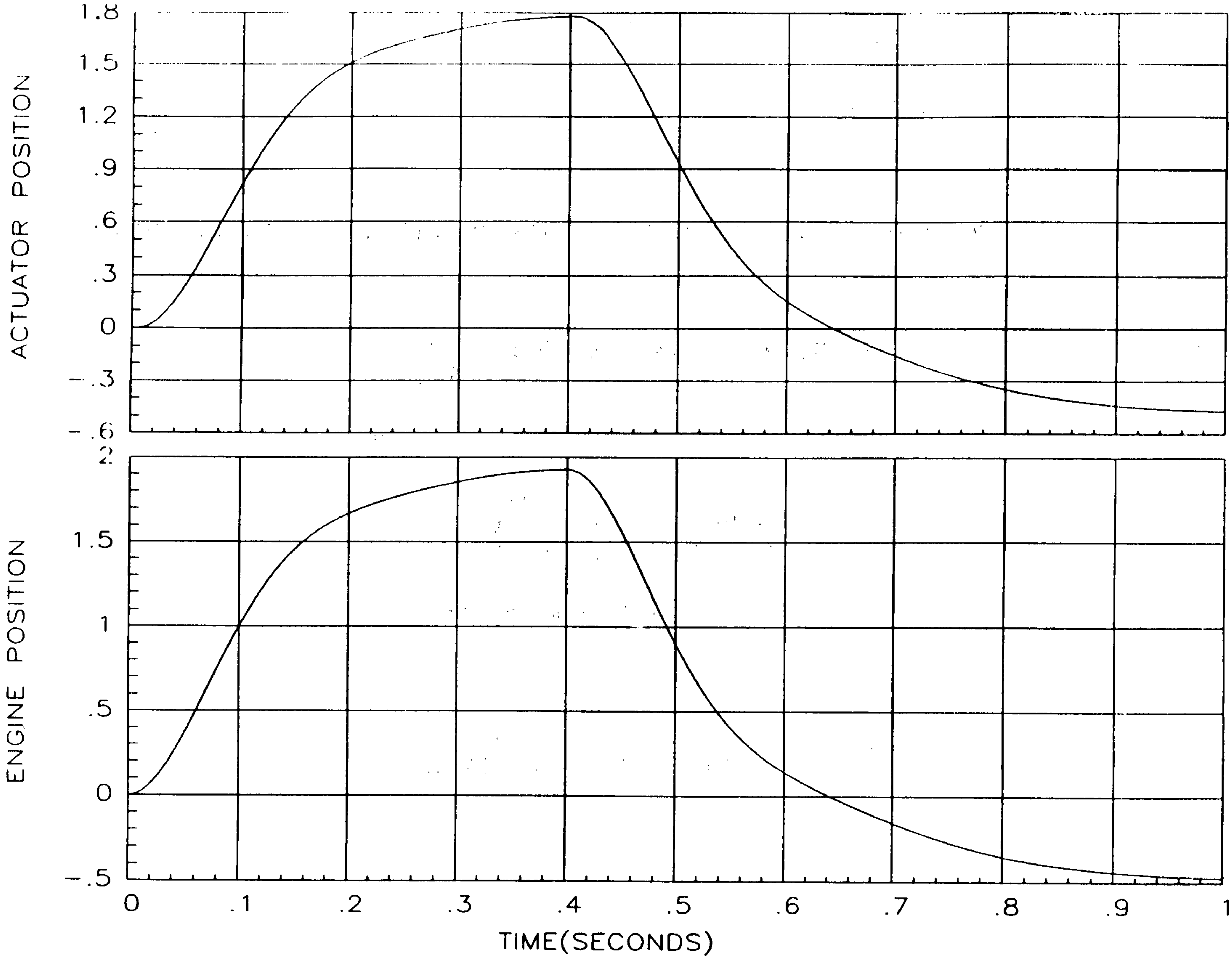
- 20, 40, 60 KIPS Amplitude
- 400 Milliseconds Duration

Notes

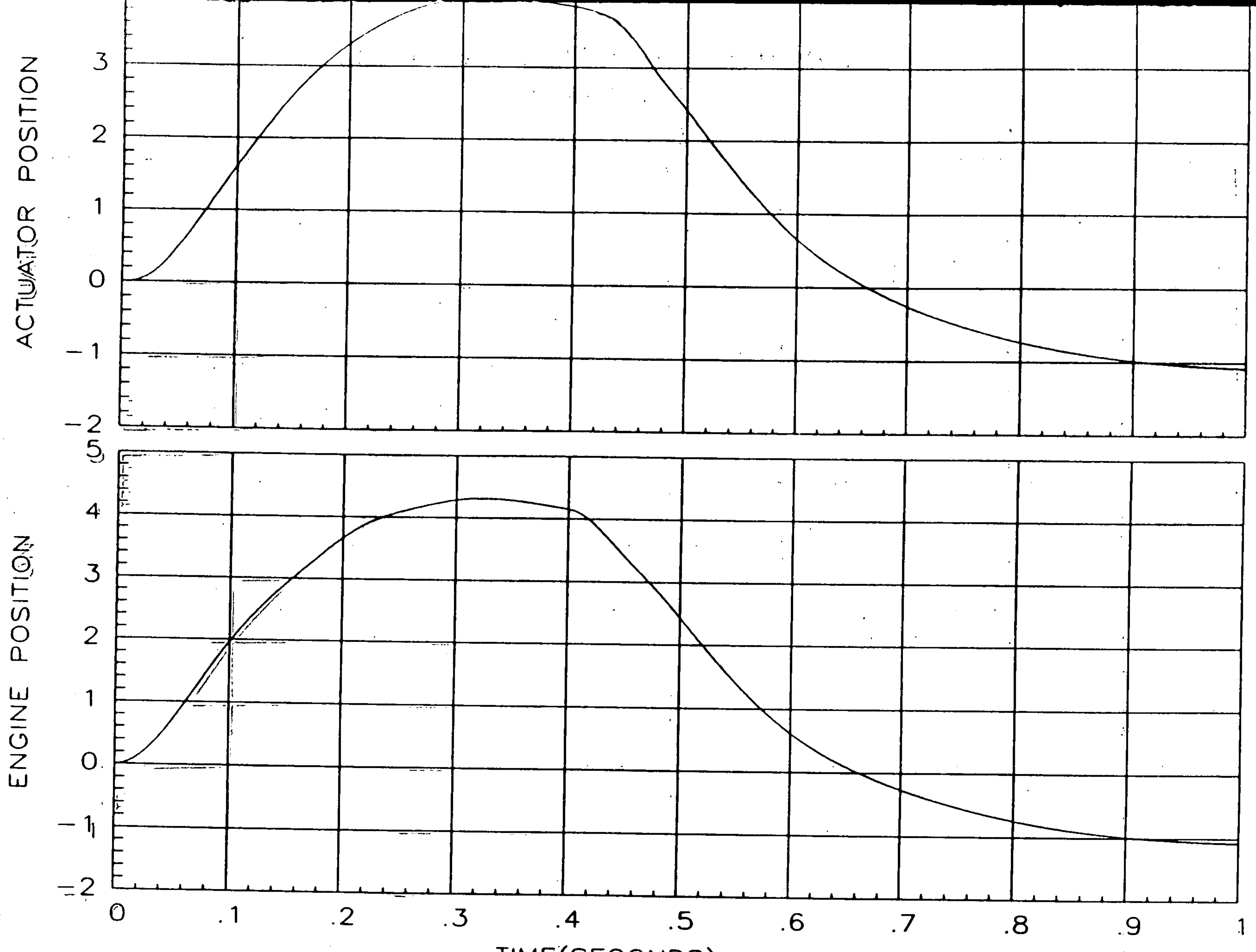
Amplitude Uncertain

Duration Unspecified In Engine Specifications

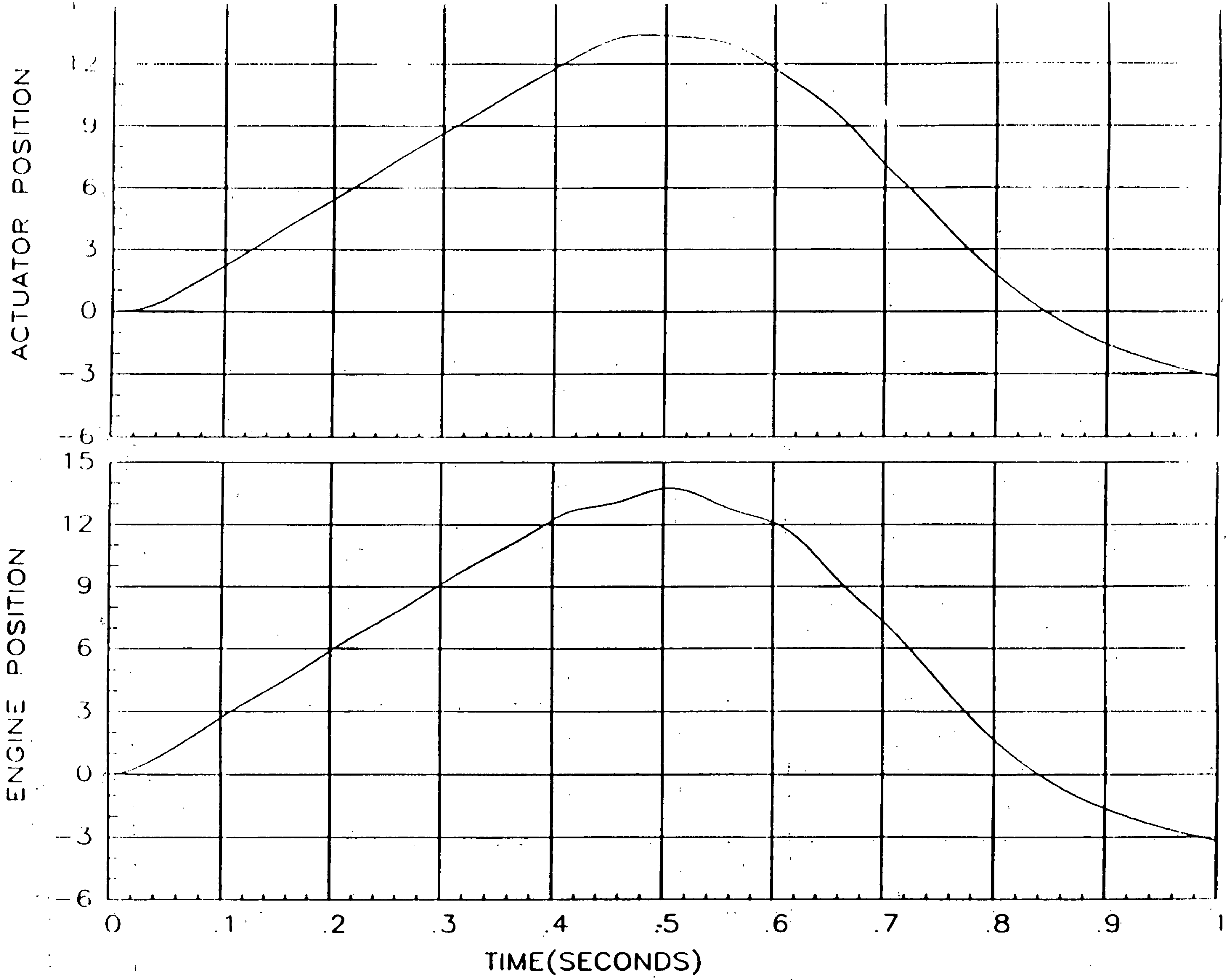
LARGEST POTENTIAL PROBLEM ARISING IN THE ENTIRE INVESTIGATION



DISTURBANCE RESPONSE (20 KIP)



DISTURBANCE RESPONSE (40 KIP)



DISTURBANCE RESPONSE (60 KIP)

A Possible Start/Stop Transient Motion Limiting Solution

It is well known that shorting a separately excited e.g. permanent magnet electric motor across its terminals inhibits motion of the motor shaft. This is due to the back emf causing large currents to flow in the armature. Discussion with MSFC electronics experts revealed that a current limited "short circuit" could be implemented with the existing MSFC controller electronics design with little modification. Given a discrete signal announcing engine start or stop then the controller could be reconfigured for some small length of time to absorb the transient and then reconfigured back to its primary or position controlling mode.

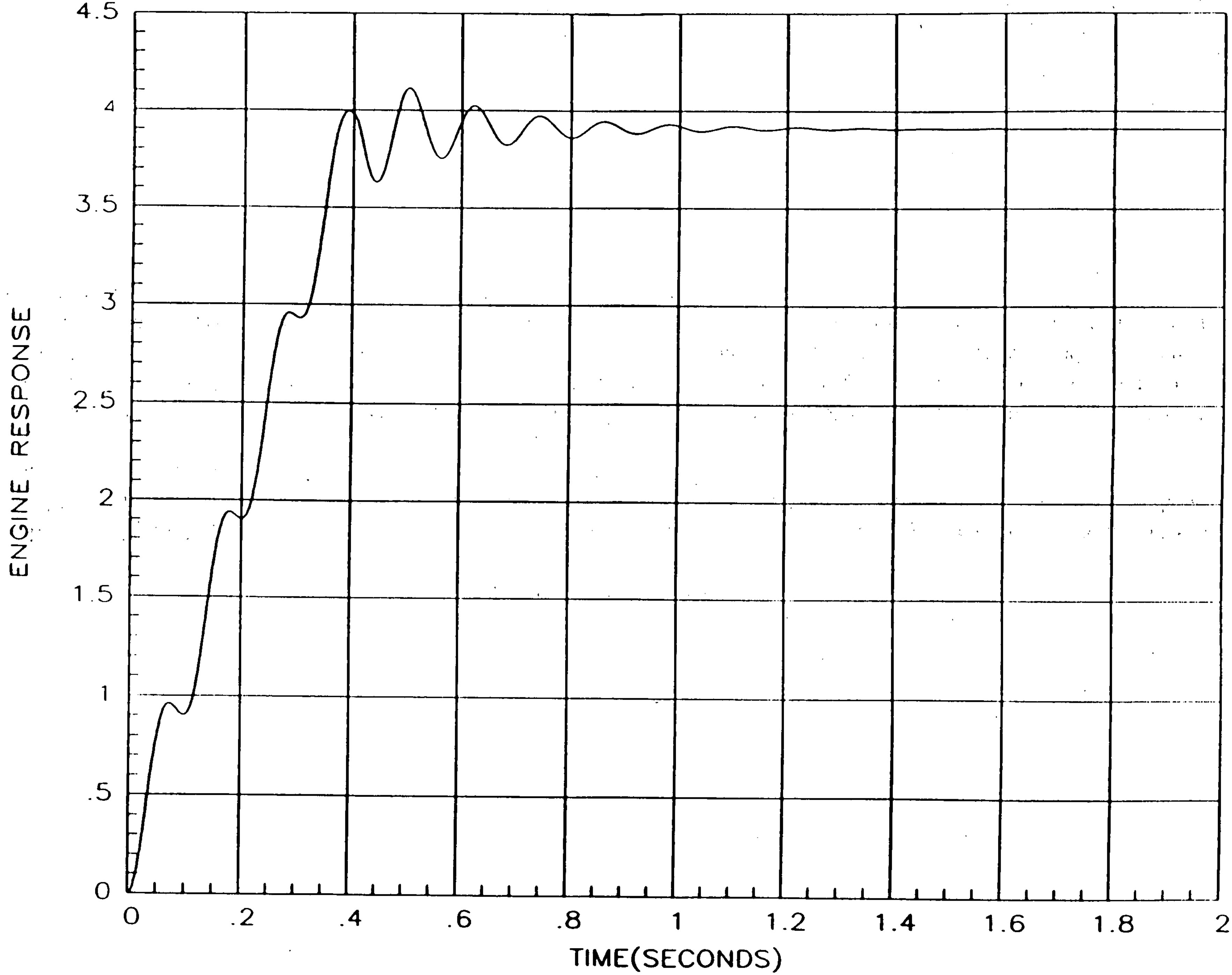
With this established the simulation was exercised with a variety of gains in the short circuit current (i.e. actuator velocity to current) loop. It was found that up to a point increasing the gain produced desired results but that higher and higher gains became progressively ineffective. However the amplitude of motion resulting was quite acceptable especially in view of the fact that discussions with the configuration designers disclosed that the engines would not hit each other (at least in the design as it then stood) regardless of the phase of the various motors' motion.

One Simple Solution to Start/Stop

Transient Phenomenon

Reconfigured Controller Approach to Controlling

Response to Start/Stop Transient



ENGINE RESPONSE TO A 60,000 LB DISTURBANCE INPUT

Mechanical Stop Design

It is generally understood that limits will be built into the command software to prevent commanding an against the stop condition for the actuator. It is also understood that limits will be built into the servo electronics so that they will not attempt to respond to commands of an against the stop nature.

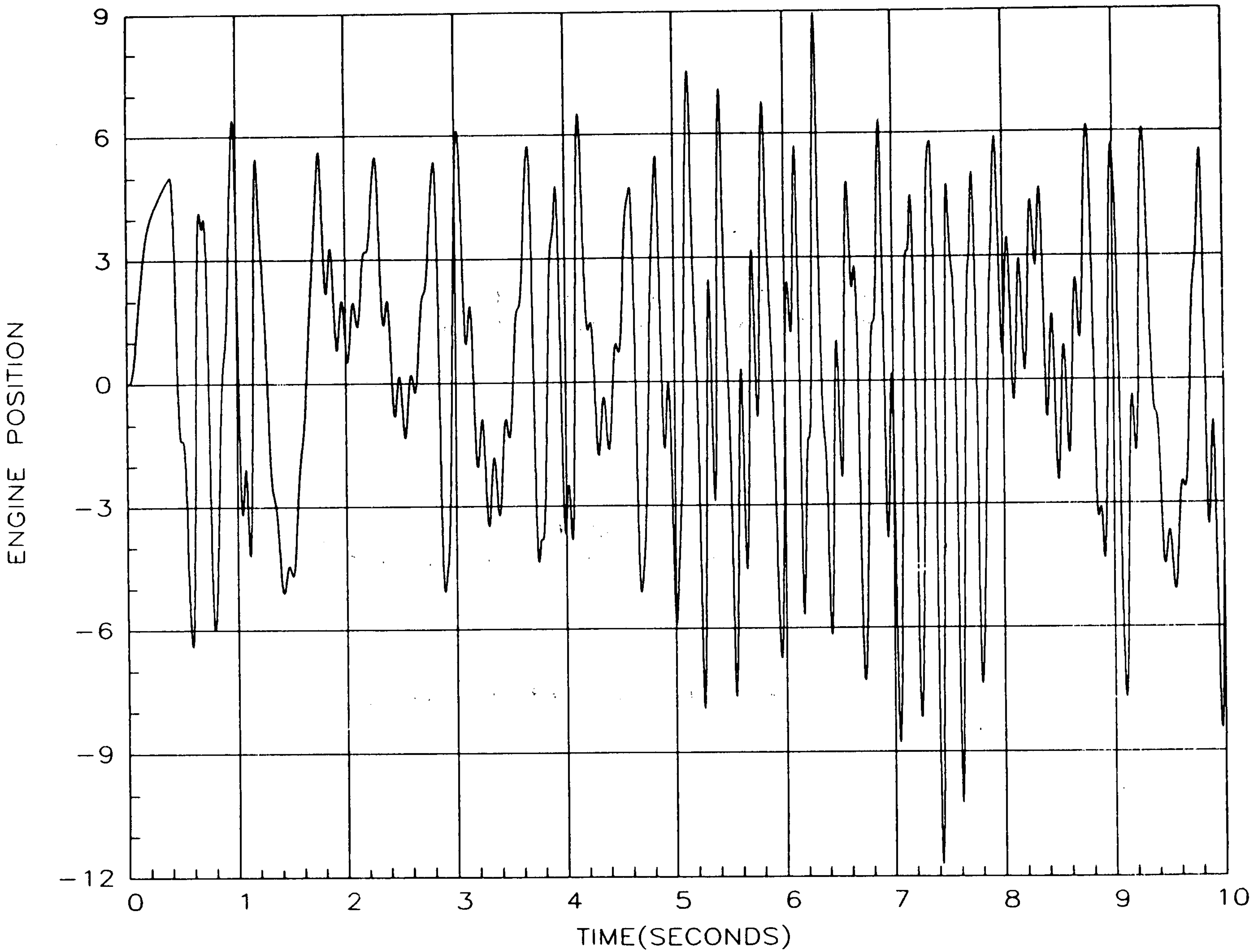
If in spite of all the foregoing precautions the actuator does go against the stop it is good practice to incorporate mechanical stops in the design which would enable the electronics to regain control or at least not allow the actuator to oscillate. To investigate this possibility the simulation was built with elastic stops whose compliance could be varied. It was found that indeed if a soft enough stop could be built the desired stable response would be obtained. This is documented in the following slides which at least bracket the desired value.

Mechanical Stop Design Considerations

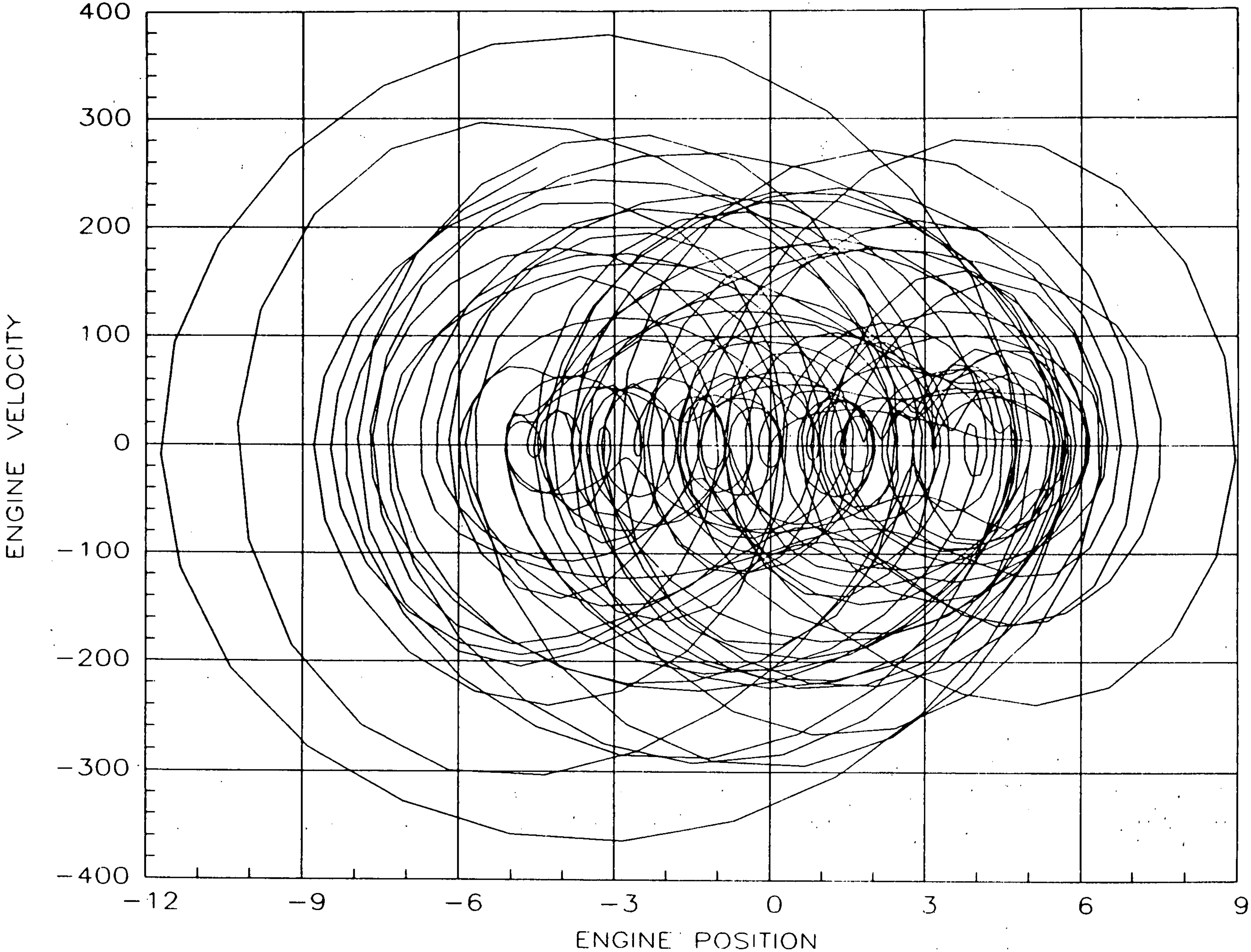
Hard or Mechanical Stop Design To Prevent Limit Cycles or Instability

Elastic Stop Assumed

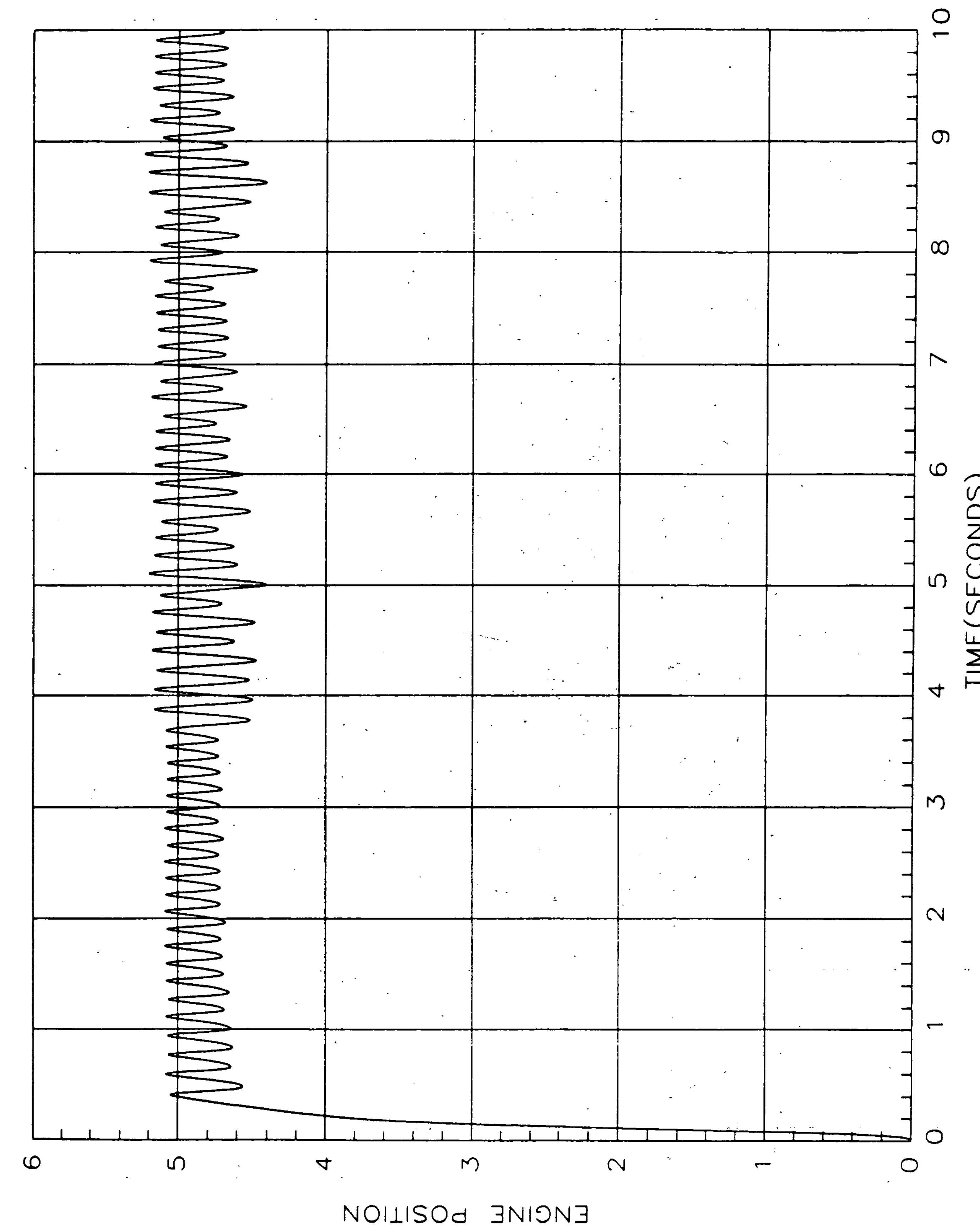
Three Different Compliance Values Were Investigated And The Results Are Displayed Below



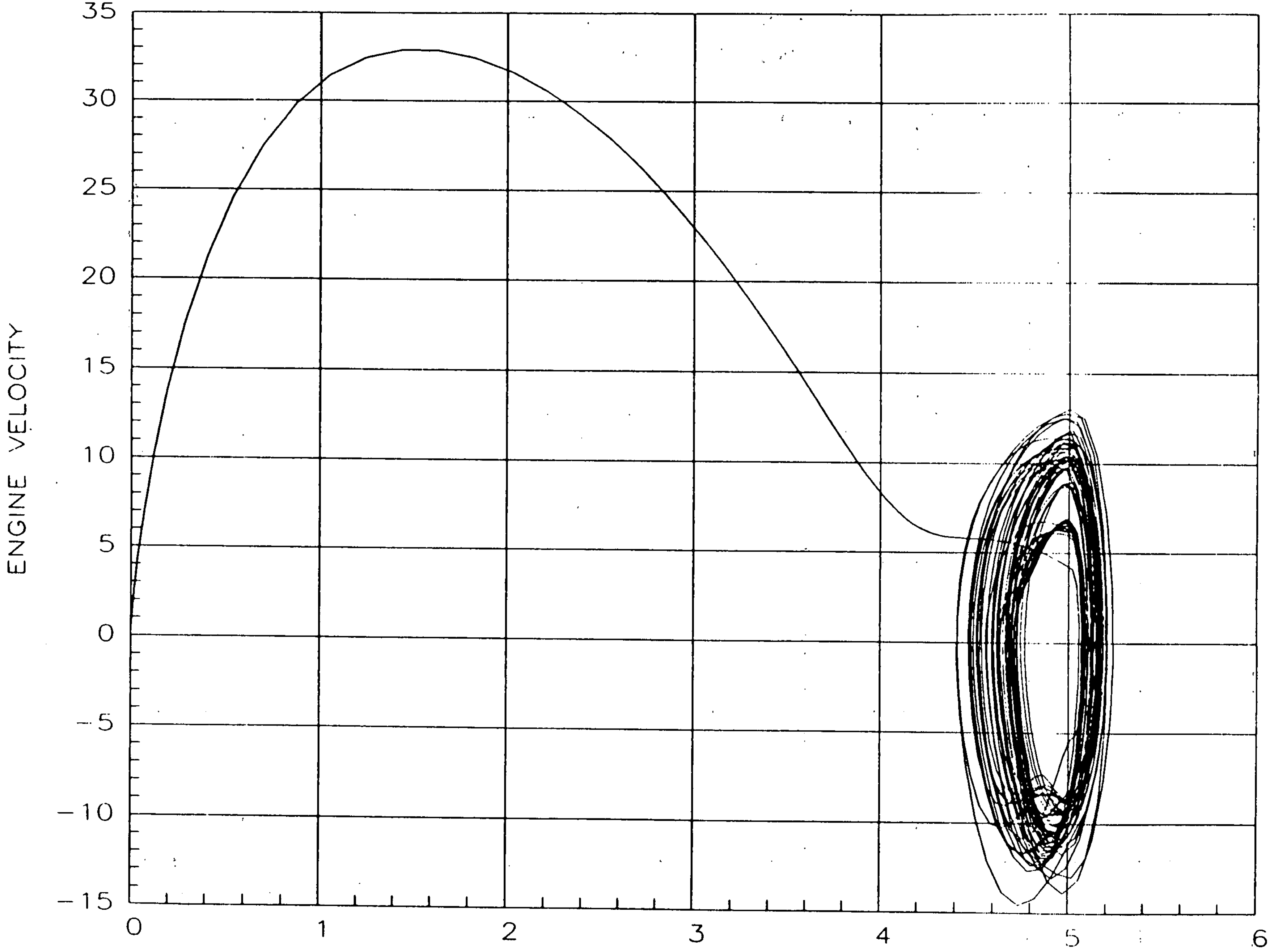
5 INCH STEP COMMAND



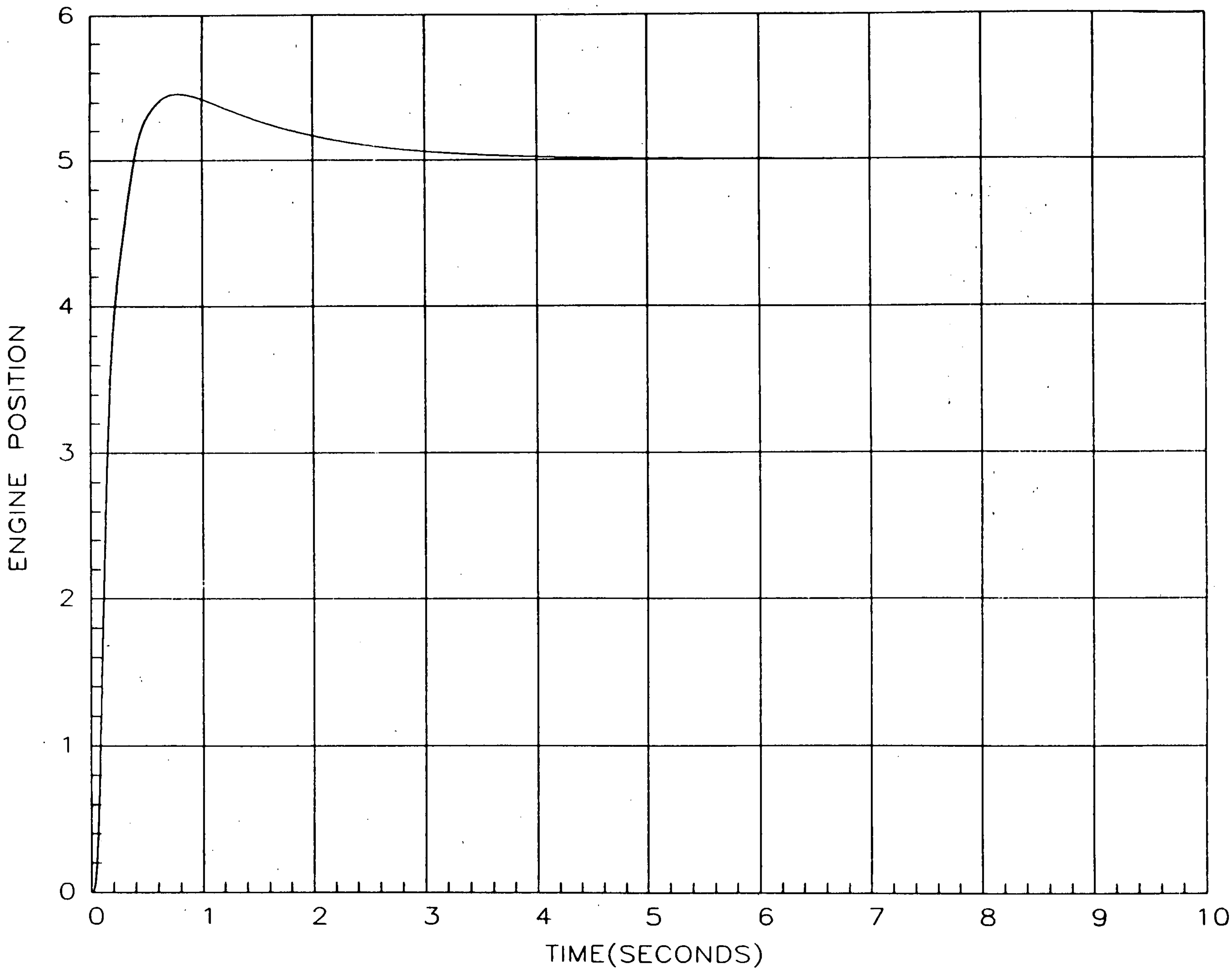
5 INCH STEP COMMAND



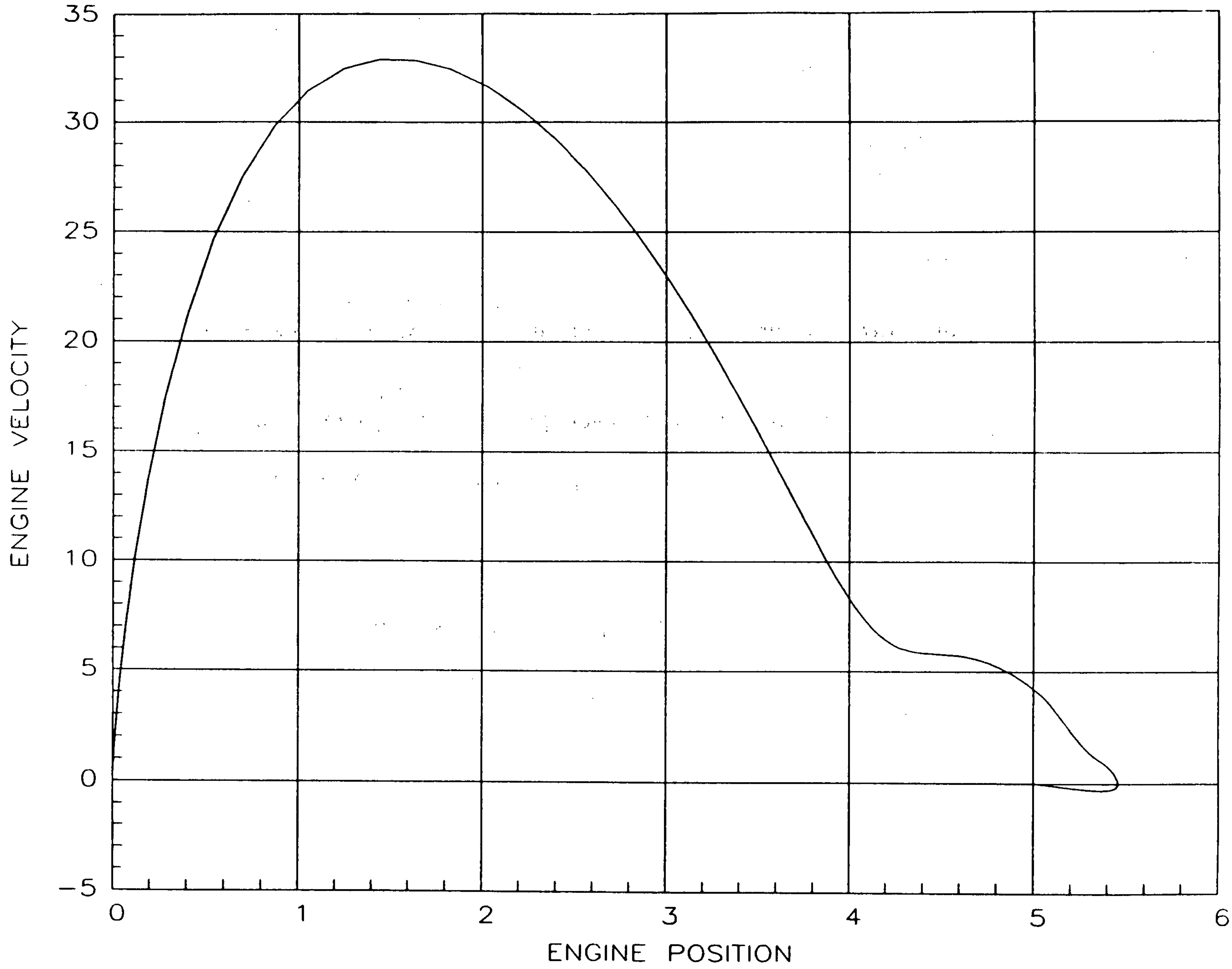
5 INCH STEP COMMAND



5 INCH STEP COMMAND



5 INCH STEP COMMAND



5 INCH STEP COMMAND

CONCLUSIONS OF TASK ONE

Electromechanical Actuator Is Feasible

Conventional Design Techniques Based on Previous Actuators Are Applicable

Serious Effort Should be Expended to Characterize Start/Stop Transient Force Parameters

TASK TWO

Based On the Results of the First Task
- **Examine Various Motor Design Approaches**
- **Design a Motor for the Actuator**

Verify Techniques Used in the Motor Design Area
- **Validating Against Existing Motors**
- **Construct/Test Designed Motor**

General Approach

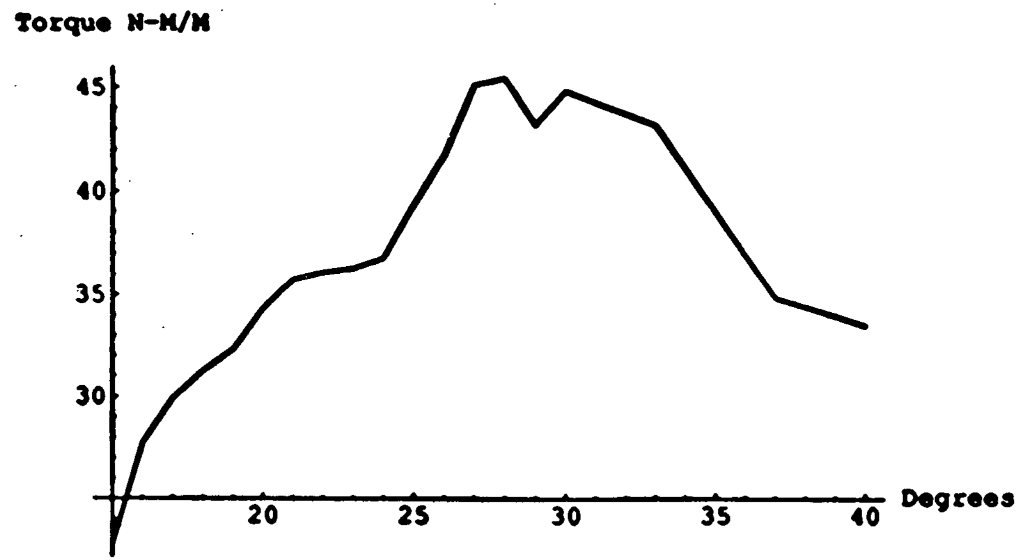
Take Conservative Approach to Initial Motor Design

Meet Motor Specifications Laid Down in Task One

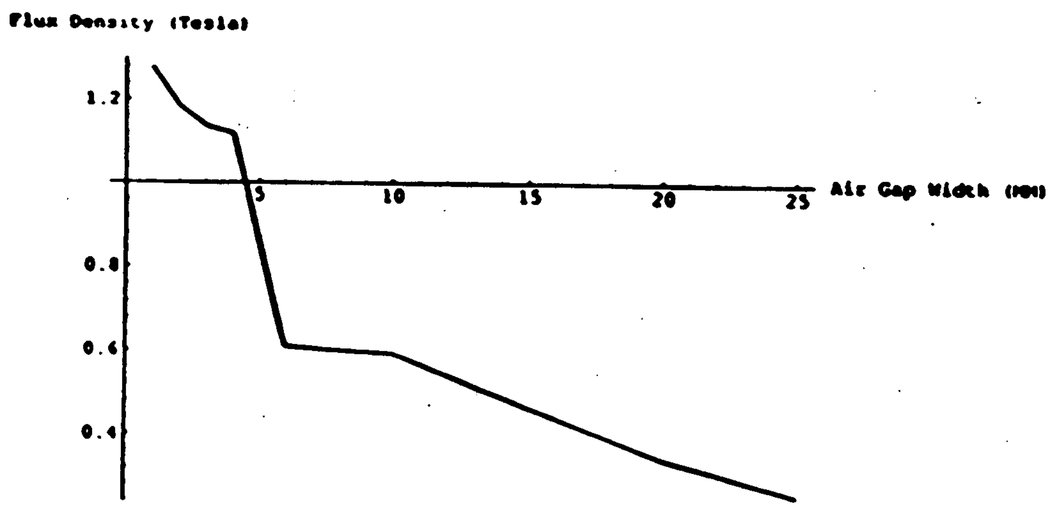
Use Finite Element Analysis Techniques Especially for the Magnetic Circuit Analyses

Allow Sufficient Difference Between Peak Back EMF and Maximum Amplifier Controlled Terminal Voltage So That Amplifier Can Control Phase Currents

Investigate Analytically Promising Unconventional or Different Approaches to Motor Configurations e.g. Slotless Motor



Torque vs. Torque Angle



Air Gap Flux Density vs. Various Radial Air Gap Widths

SESSION III

ELA CONTROL ELECTRONICS

ORGANIZATION EB24 CHART NO.	MARSHALL SPACE FLIGHT CENTER *Electromechanical Actuator Electronic Controller*	NAME *Justino Montenegro* DATE *September 29, 1992*

25KW

ELECTRONIC CONTROLLER

FOR THE 25HP EMA

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ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
EB24	***Electromechanical Actuator Electronic Controller***	***Justino Montenegro***
CHART NO		DATE ***September 29, 1992***

ELECTROMECHANICAL ACTUATOR (EMA) ELECTRONIC CONTROLLER

STME EMA PERFORMANCE REQUIREMENTS

- STALL FORCE: 60,000 LBS
- RATED LOAD: 40,000 LBS
- EFFECTIVE MOMENT ARM: 29.8 INCHES
- RATED VELOCITY: 5.0 IN./SEC.
- DYNAMIC FORCE: 40,000 LBS AT 5 IN./SEC. = 30.3HP
- STROKE: +/- 4.4 INCHES
- ACCELERATION: 2 RAD/SEC^2
- BANDWIDTH: 4Hz AT +/-2% OF FULL STROKE
- REDUNDANCY: FAIL OPERATE
  3 CHANNELS REQUIRED
- SUPPLY VOLTAGE: 270 VDC, NOMINAL
  ACCEPTABLE TO CORONA EXPERTS

DERIVED REQUIREMENTS

- EQUIVALENT GEAR RATIO (SPUF + SCREW): 8,000: 1 (TYPICAL)
- MAXIMUM MOTOR SPEED: 12,000 - 14,000 RPM
- PEAK POWER: 87K WATTS TOTAL

  29 K WATTS/CHANNEL

- PEAK SUPPLY CURRENT: 365 AMPS @ 240VDC (3 CHANNELS)
- MOTOR ROTOR INERTIA: 3×10^{-4} FT LB SEC^2

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
EB24	***Electromechanical Actuator Electronic Controller***	***Justino Montenegro***
CHART NO		DATE **September 29, 1992**

CANDIDATE MOTOR TYPES

- PERMANENT MAGNET BRUSHLESS DC
- VARIABLE FREQUENCY INDUCTION
- SWITCHED RELUCTANCE

BASELINE MOTOR:

PERMANENT MAGNET BRUSHLESS DC (PMBDC)

- HIGHEST OUTPUT POWER TO WEIGHT RATIO
- HIGHEST EFFICIENCY
- HIGH TORQUE TO INERTIA RATIO
- IDEAL THERMAL CHARACTERISTICS - NO HEAT IN ROTOR
- FULLY AND EASILY CONTROLLED
- POTENTIAL FOR HANDLING ENGINE START-UP TRANSIENT BY SHORTING WINDINGS
- DRAG CAUSED BY SHORTED WINDING OR SHORTED TRANSISTOR IS LESS THAN HARD OVER FAILURE.
- PM MOTOR/FLYWHEEL FLOATING ON POWER BUS HAS POTENTIAL FOR SUPPLYING CURRENT SURGE.

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
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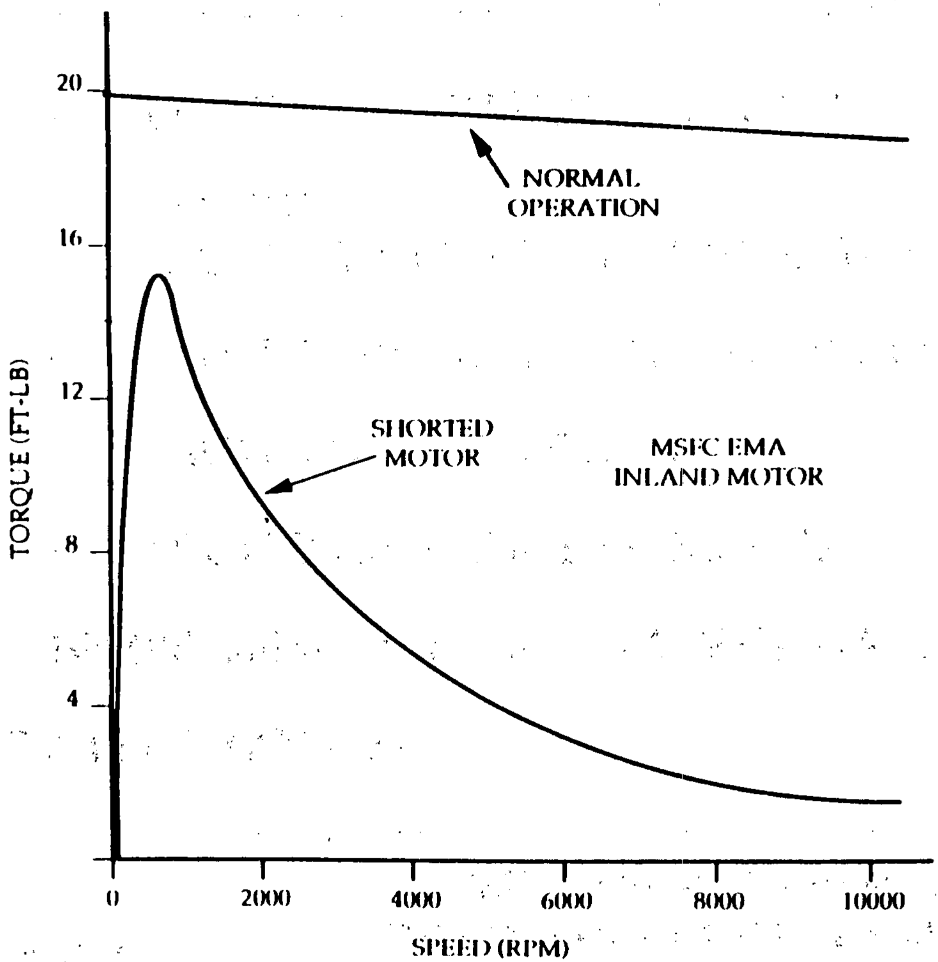
CHART NO		DATE ***September 29, 1992***

SHORTED MOTOR PERFORMANCE



TYPICAL PERFORMANCE FOR EMA'S BY

AEROJET/MSFC

HR/TEXTRON/MSFC

MOOG

AIR RESEARCH/J-STARS

MSFC(2)

HONEYWELL

ELECTRONIC CONTROLLER TYPES

- 6 TRANSISTOR, 6 STEP, PULSE WIDTH MODULATED (PWM)
- 6 TRANSISTOR, SINUSOIDAL PWM
- 8 TRANSISTOR, 6 STEP, PWM

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
EB24	***Electromechanical Actuator Electronic Controller***	***Justino Montenegro***
CHART NO		DATE ***September 29, 1992***

6 TRANSISTOR SINUSOIDAL PWM

REQUIRES LINEAR RESOLVER

HIGHER BANDWIDTH

MOST EFFICIENT

MOTORS NOT READILY AVAILABLE FOR TESTING

Electromechanical Actuator Electronic Controller

Justino Montenegro

DATE September 29, 1992

SIX TRANSISTOR, 6 STEP PWM CONTROLLER

- SIMPLEST
- SENSITIVE TO MOTOR L/R AND LEAD LENGTH
- REQUIRES HIGH FREQUENCY SWITCHING
- ASSOCIATED TRANSISTORS HAVE HIGH ON LOSS, LOWER SWITCHING LOSS
- EFFICIENCY IS IMPORTANT
- CONTROLLER SELF STANDING (NOT ON COLD PLATE): MUST INCLUDE ENOUGH HEAT SINK WEIGHT TO KEEP TEMPERATURE AT A SAFE LEVEL.

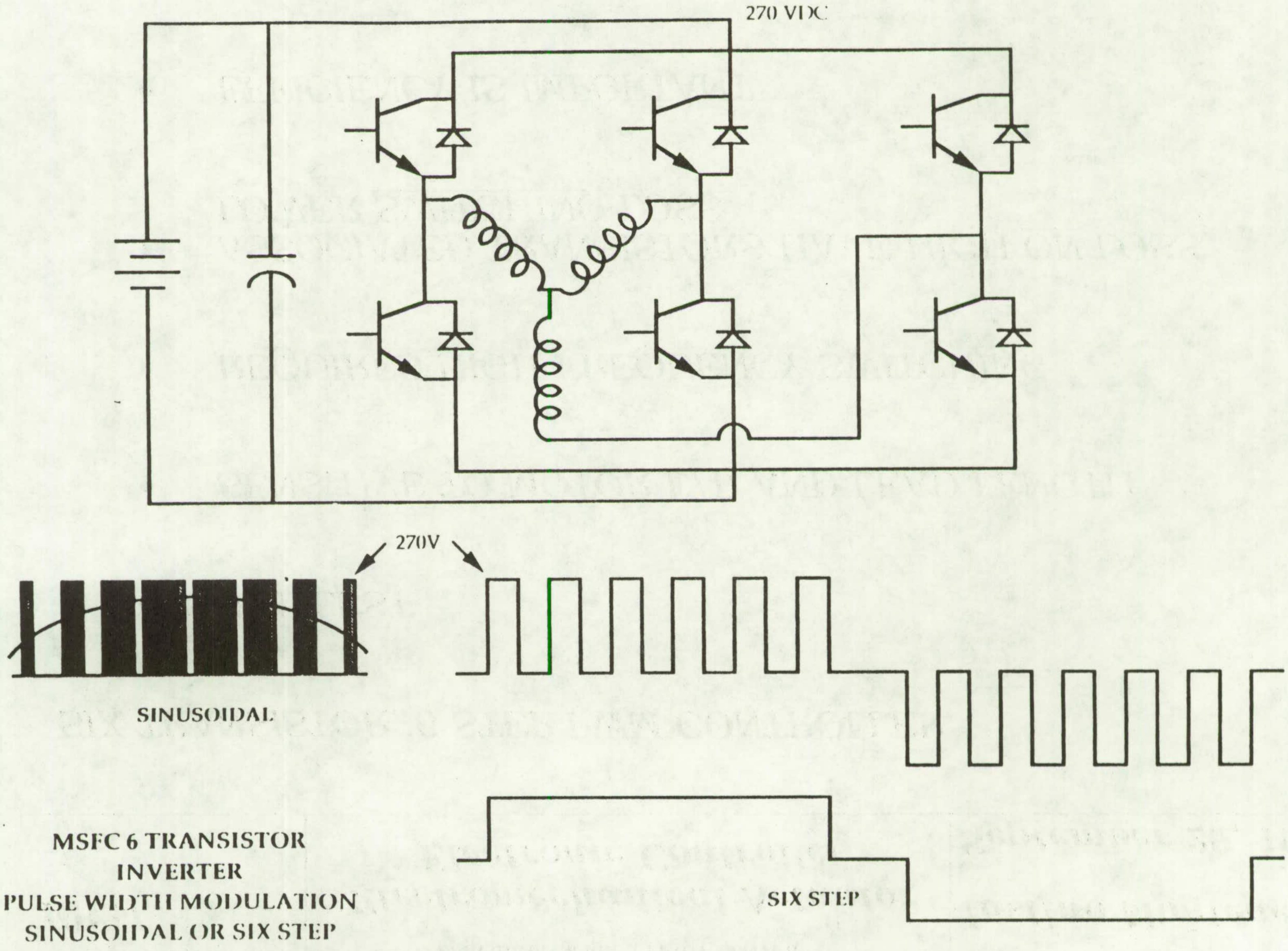
EB24

MARSHALL SPACE FLIGHT CENTER

Electromechanical Actuator Electronic Controller

Justino Montenegro

September 29, 1992



MSFC 6 TRANSISTOR
INVERTER
PULSE WIDTH MODULATION
SINUSOIDAL OR SIX STEP

EIGHT TRANSISTOR, 6 STEP PWM CONTROLLER

- LEAST SENSITIVE TO MOTOR L/R
- LOW SWITCHING FREQUENCIES
- ASSOCIATED TRANSISTORS HAVE LOW ON LOSS, HIGHER SWITCHING LOSS
- EFFICIENCY IS IMPORTANT
- CONTROLLER SELF STANDING (NOT ON COLD PLATE): MUST INCLUDE ENOUGH HEAT SINK WEIGHT TO MAINTAIN TEMPERATURE AT A SAFE LEVEL.

* ALL CONTROLLERS INCLUDE ONE EXTRA POWER TRANSISTOR FOR MANAGING ENERGY DURING BRAKING (KINETIC ENERGY)

ORGANIZATION

CHART NO. **EB24**

MARSHALL SPACE FLIGHT CENTER

Electromechanical Actuator Electronic Controller

Justino Montenegro

DATE **September 29, 1992**

EIGHT TRANSISTOR INVERTER

LOW SPEED SWITCHING 2 KHZ TYP.

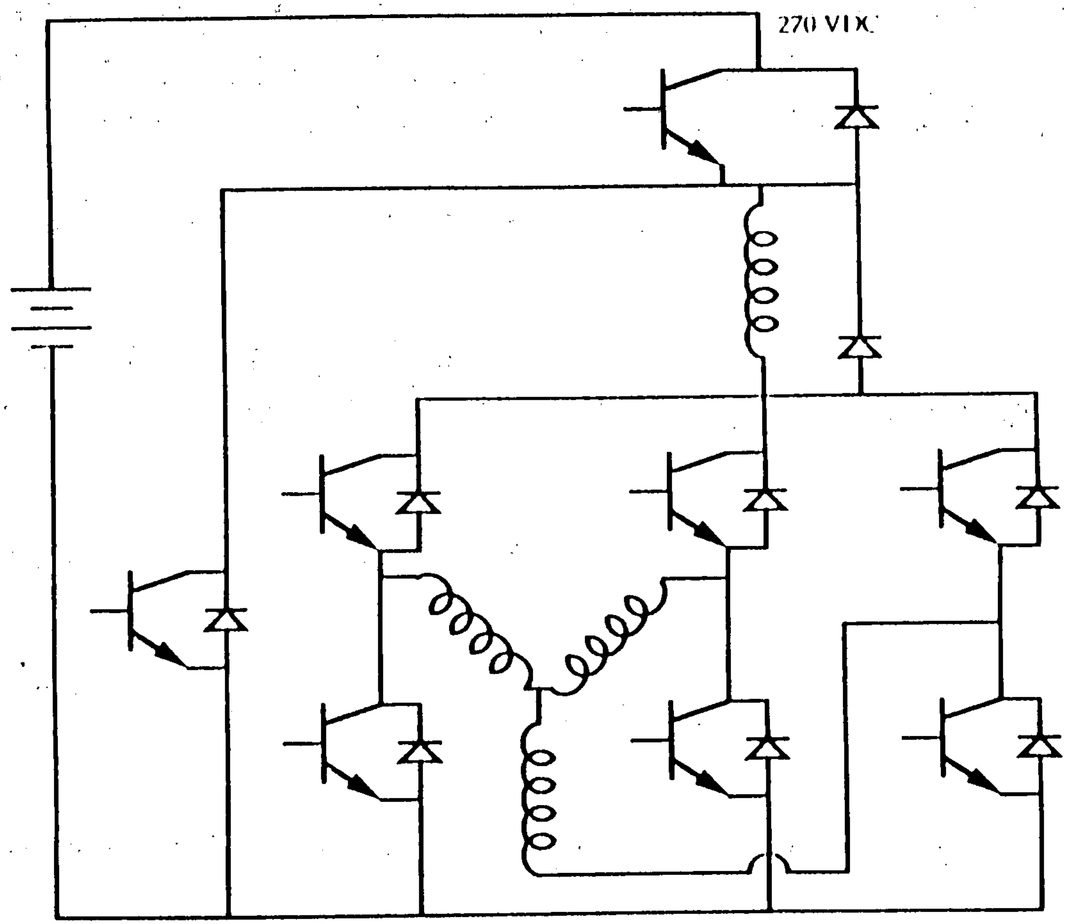
NOT SENSITIVE TO MOTOR L/R

SIX STEP ONLY

LOWER CONDUCTION LOSS

MORE PARTS

EFFICIENCY >95%



MSFC 8 TRANSISTOR
6 STEP INVERTER
PULSE WIDTH MODULATION

Electromechanical Actuator Electronic Controller

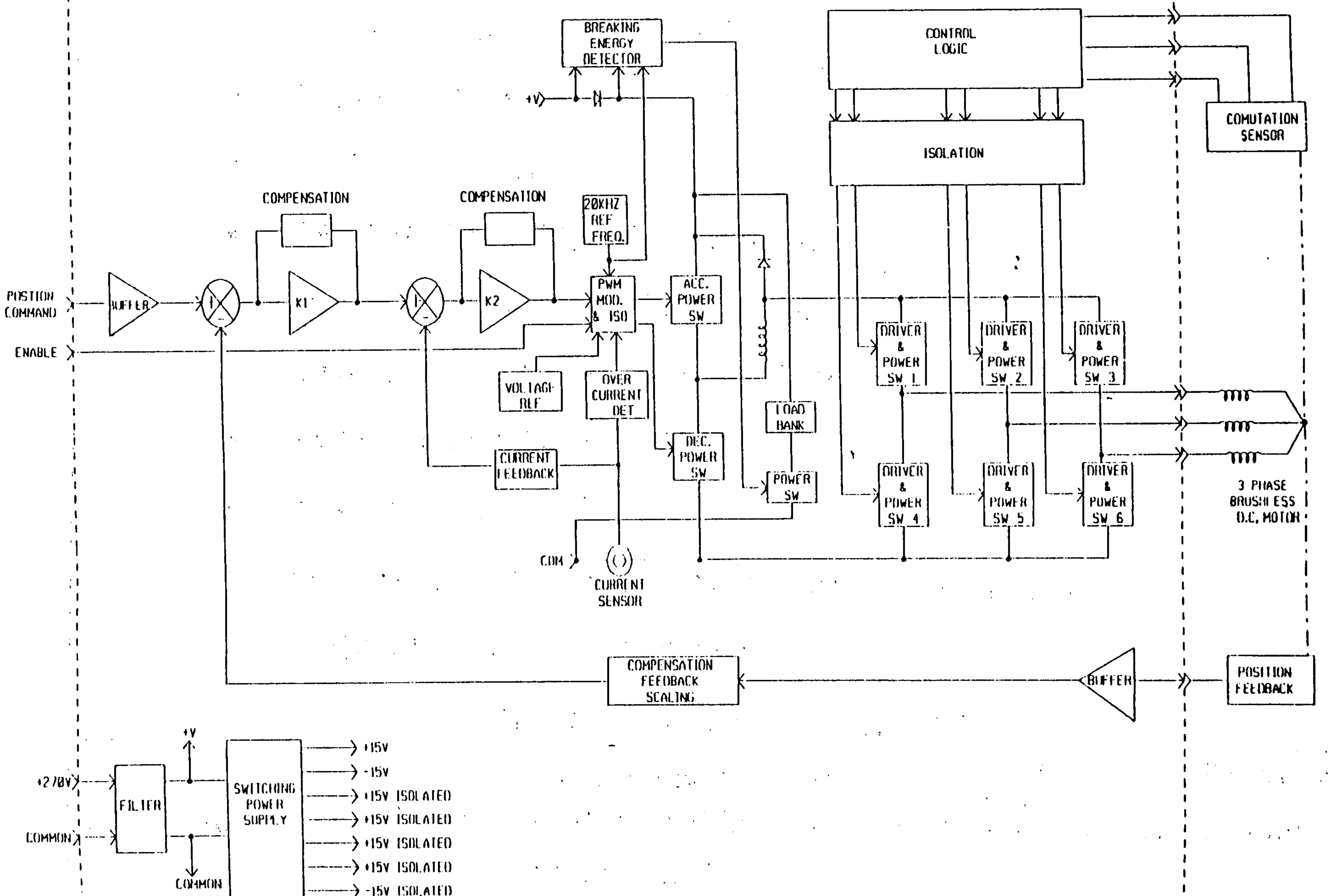
NAME
Justino Montenegro

DATE
September 29, 1992

25KW CONTROLLER FEATURES

- CURRENT LOOP OPERATION
- POSITION LOOP OPERATION WITH RESOLVER
- 14KHZ PWM FREQUENCY
- FOUR QUADRANT OPERATION
- OPTICALLY ISOLATED IGBT DRIVERS
- ADJUSTABLE CURRENT LIMIT
- OPERATING VOLTAGE: 270VDC
- RATED CURRENT: 100 AMPS
- PEAK CURRENT: 150 AMPS
- POWER SWITCHES: IGBT'S
- DYNAMIC BRAKING LOAD BANK (CONTROLLED)
- ANALOG LOW POWER ELECTRONICS

25 KW SERVO DRIVE SYSTEM - BLOCK DIAGRAM



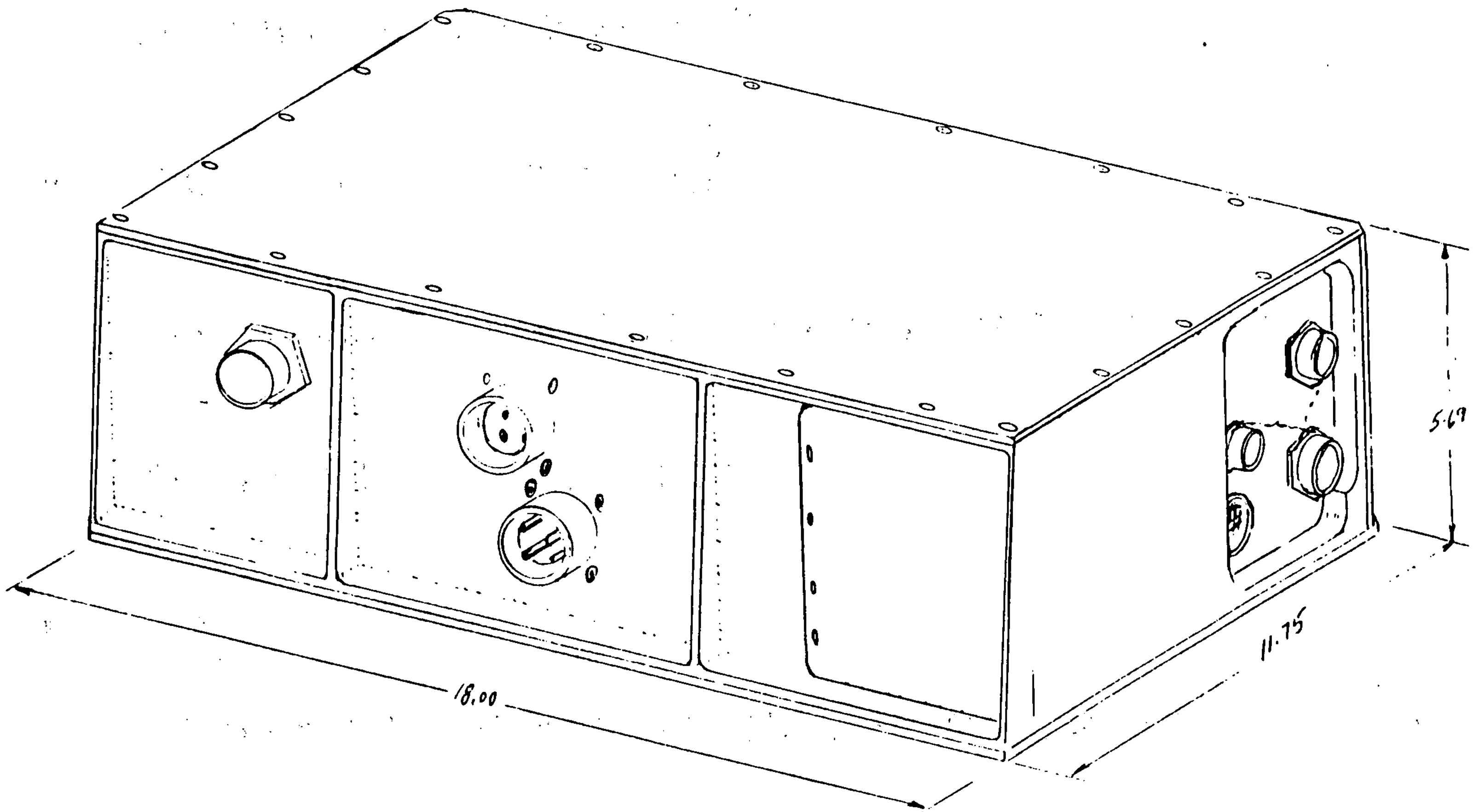
ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
EB24	***Electromechanical Actuator Electronic Controller***	***Justino Montenegro***
CHART NO		DATE ***September 29, 1992***

25HP MOTOR *

- PERMANENT MAGNET, 3 PHASE BRUSHLESS D. C. MOTOR
- 12 POLE
- SAMARIUM COBALT MAGNETS
- HALL EFFECT DEVICES FOR COMMUTATION SENSING
- 9200 RPM NO LOAD SPEED
- EFFICIENCY (MEASURED) >92%
- 4000 OZ-IN @ 7000 RPM

* OFF THE SHELF, INEXPENSIVE, NOT OPTIMIZED FOR EFFICIENCY

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
EB24	***Electromechanical Actuator Electronic Controller***	***Justino Montenegro***
CHART NO.		DATE **September 29, 1992**

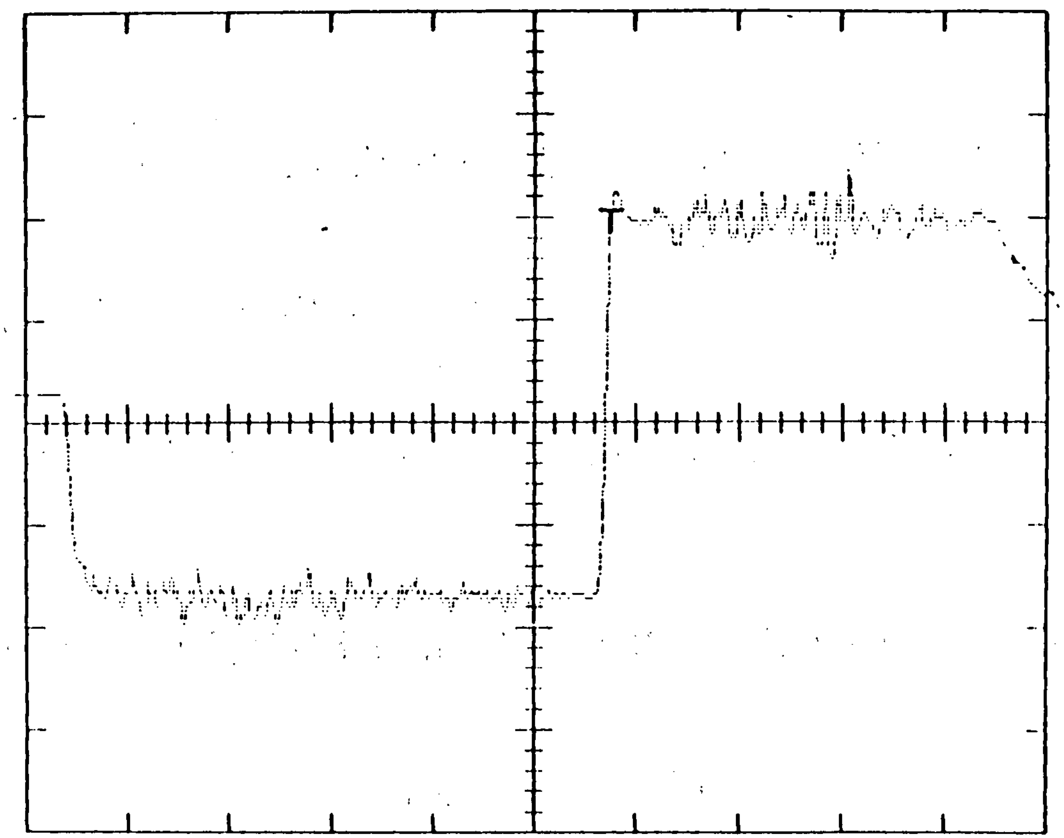


25KW CONTROLLER ENCLOSURE

TEST RESULTS

- CONTROLLER (POWER INVERTER) HAS BEEN DEMONSTRATED AT 54 HP PEAK
- RESPONSE TIME: 130m SEC, FROM 7,000 RPM TO -7,000 RPM
- CONTROLLER EFFICIENCY: >95%
- LINEARITY TEST WITH AND WITHOUT INTEGRATOR IN POSITION LOOP

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	
EB24 CHART NO	***Electromechanical Actuator Electronic Controller***	***Justino Montenegro*** DATE ***September 29, 1992***

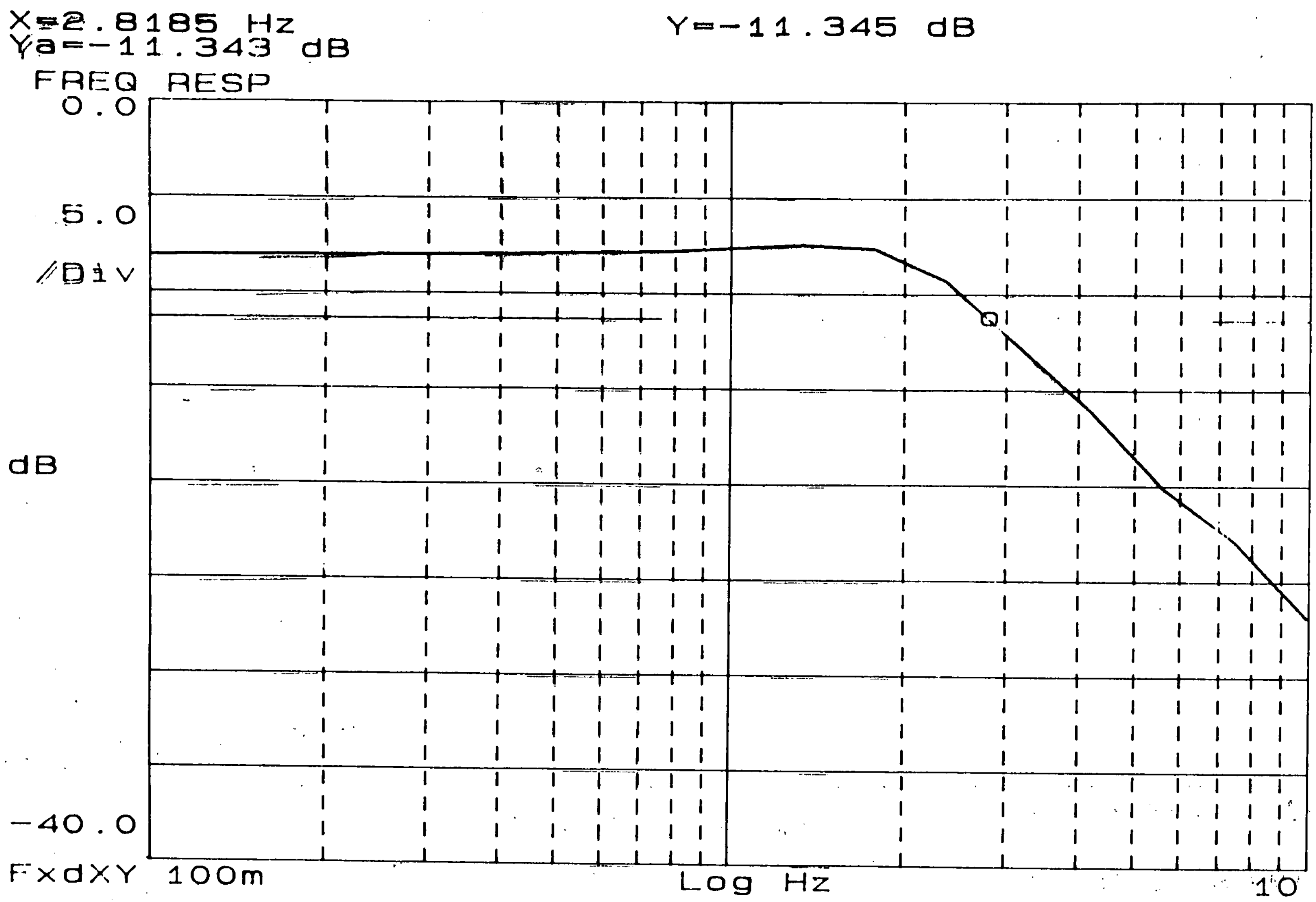


20MS/DIV

FREE RUNNING MOTOR DECELERATION/ACCELERATION CURRENT (50A/DIV)
(-9250 RPM TO + 9250 RPM)

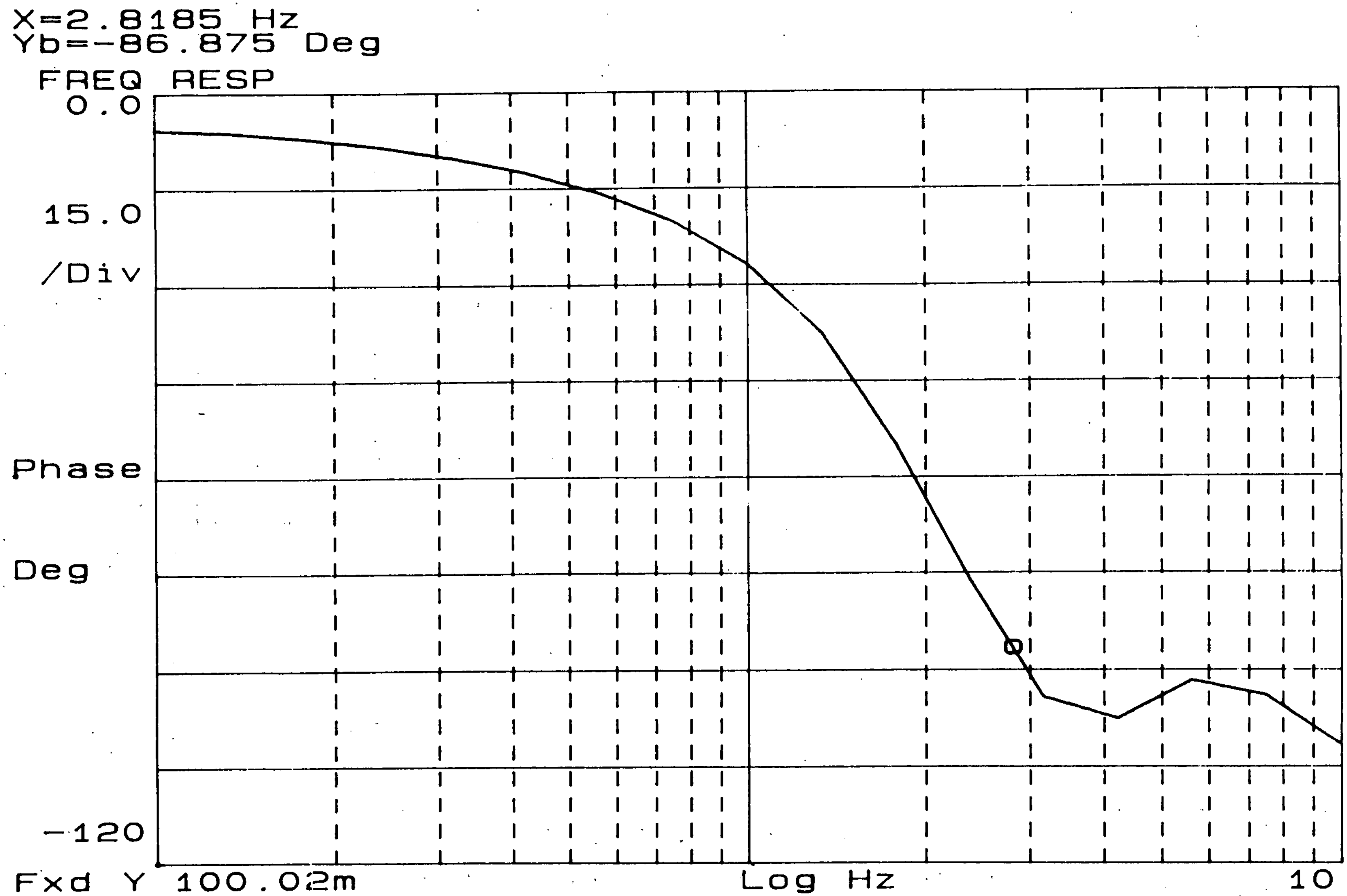
BATTERY VOLTAGE: 270VDC

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
EB24	***Electromechanical Actuator***	***Justino Montenegro***
CHART NO	***Electronic Controller***	DATE
		September 29, 1992



2% COMMAND

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
EB24	Electromechanical Actuator Electronic Controller	Justino Montenegro
CHART NO		DATE September 29, 1992



2% COMMAND

ORGANIZATION **EB24**

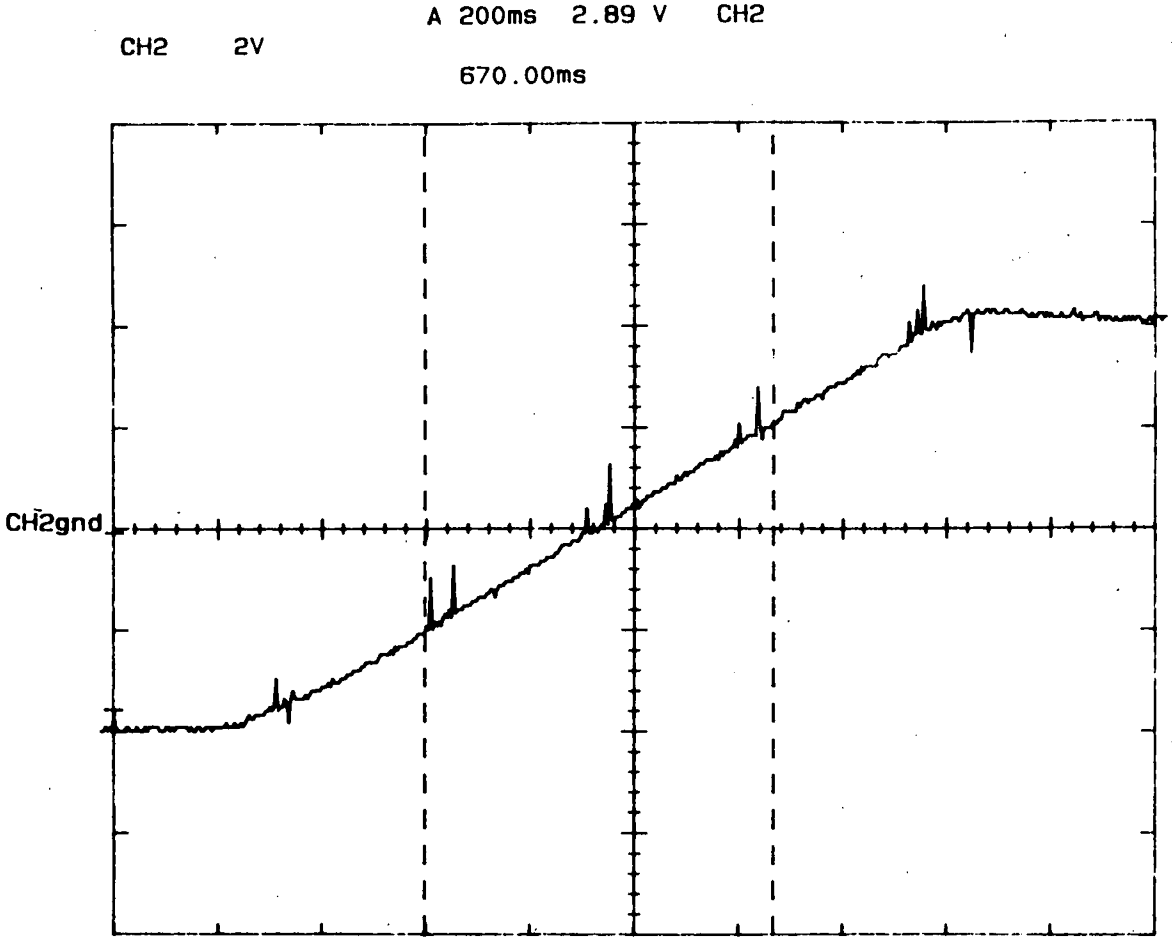
CHART NO

MARSHALL SPACE FLIGHT CENTER

Electromechanical Actuator Electronic Controller

NAME ***Justino Montenegro***

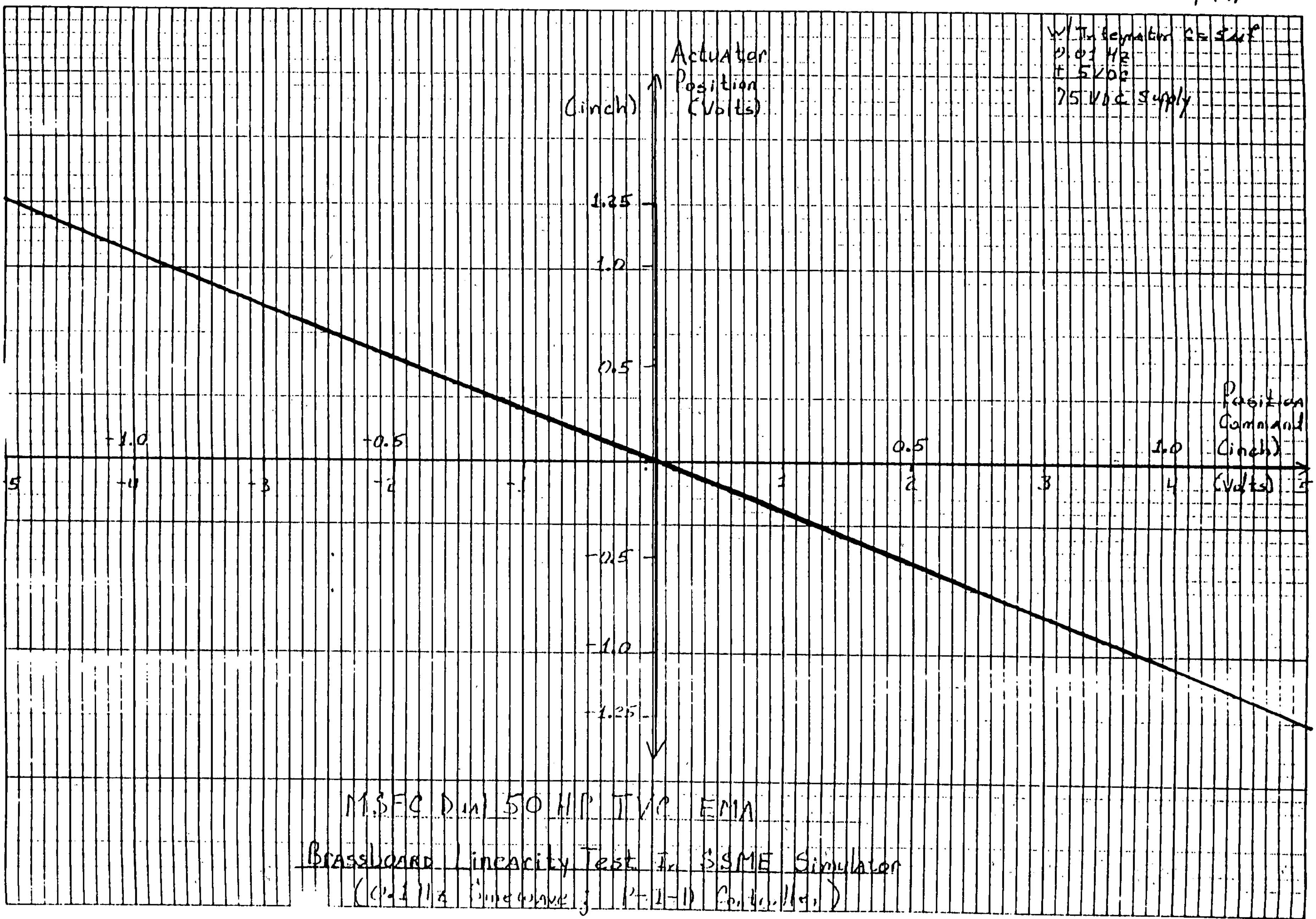
DATE ***September 29, 1992***



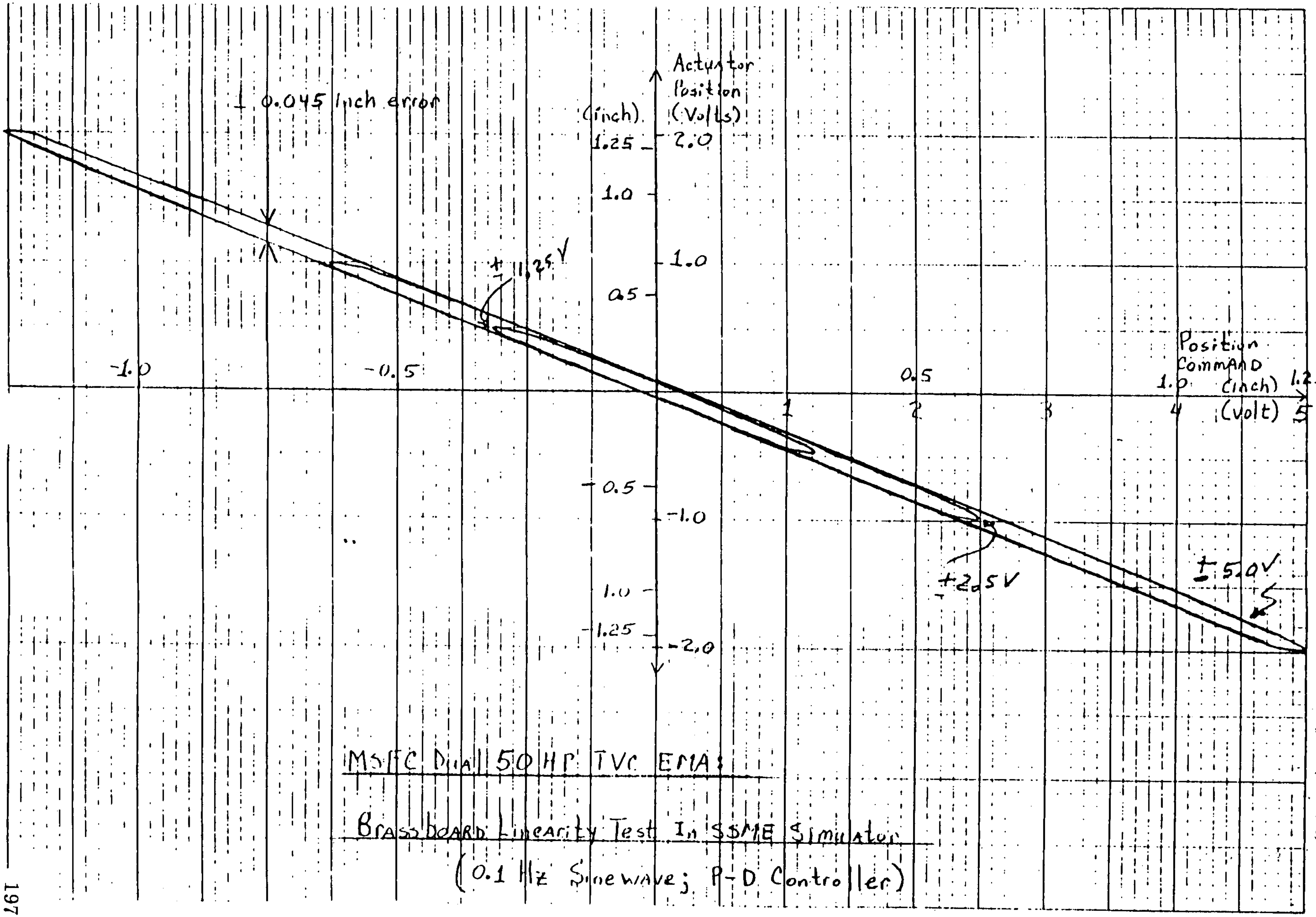
STEP RESPONSE

VERTICAL SCALE: 1.25 IN/DIV

11/8/91


W/ Tx Generator C = 5 uf
0.01 Hz
± 5 Vdc
75 Vdc Supply
Actuator Position (Volts)
(inch)
1.25
1.0
0.5
-0.5
-1.0
-1.25
Position Command (inch)
(Volts)
-1.0
-0.5
0.5
1.0
-5
-4
-3
-2
-1
1
2
3
4
5
MSFC Dual 50 HP TVC EMA
Brassboard Linearity Test In SSME Simulator
(0.1 Hz Sinewave; P-I-D Controller)

11/7/91



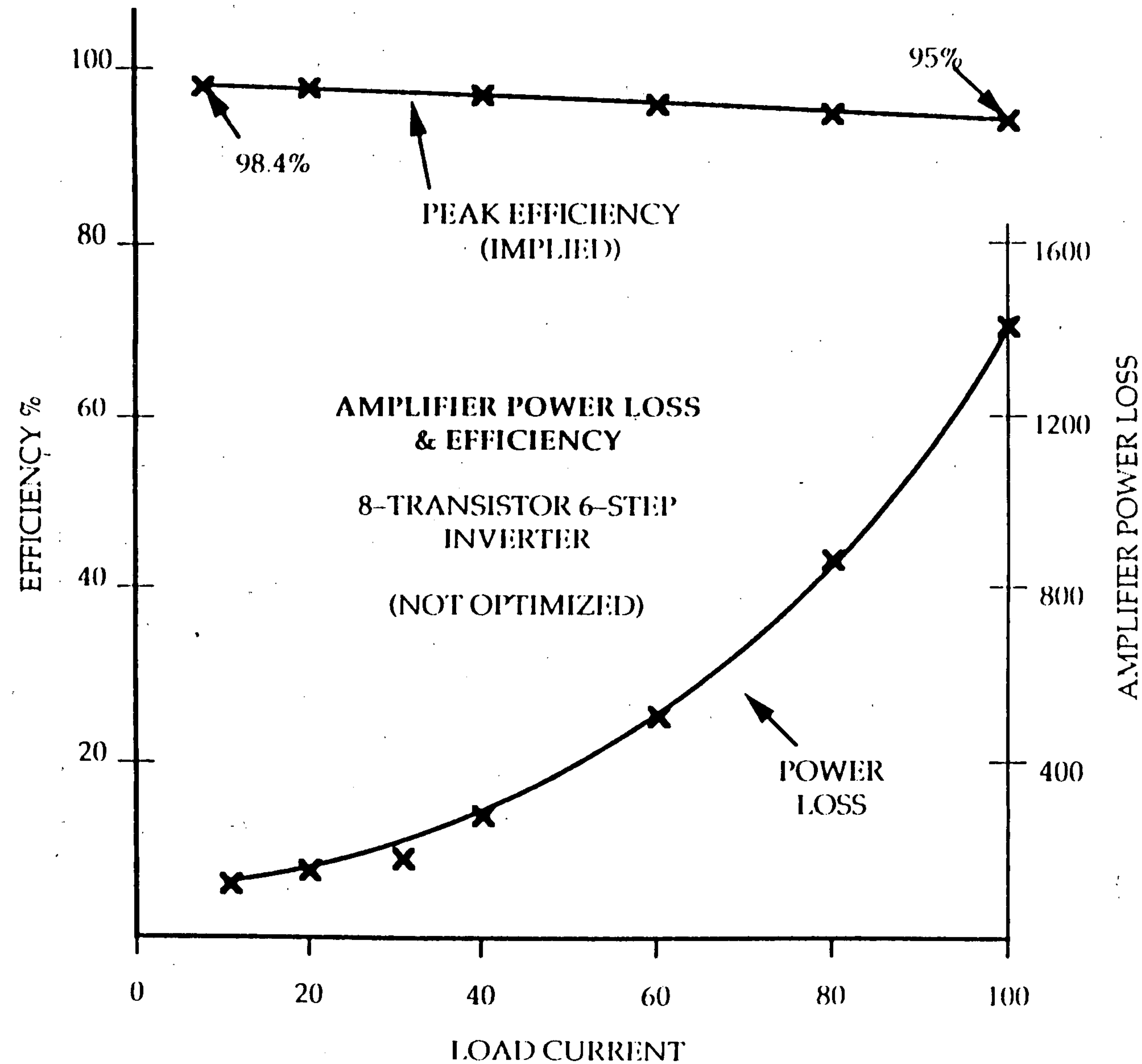
± 0.045 Inch error
Actuator Position
(inch)
(Volts)
1.25
2.0
1.0
1.0
0.5
± 1.25V
-1.0
-0.5
0.5
Position COMMAND
1.0
(inch)
1.25
1
2
3
4
(volt)
5
0.5
-1.0
± 2.5V
± 5.0V
1.0
1.25
-2.0
MSFC Dual 50 HP TVC EMA:
Brassboard Linearity Test In SSME Simulator
(0.1 Hz Sinewave; P-D Controller)

ORGANIZATION **EB24** CHART NO

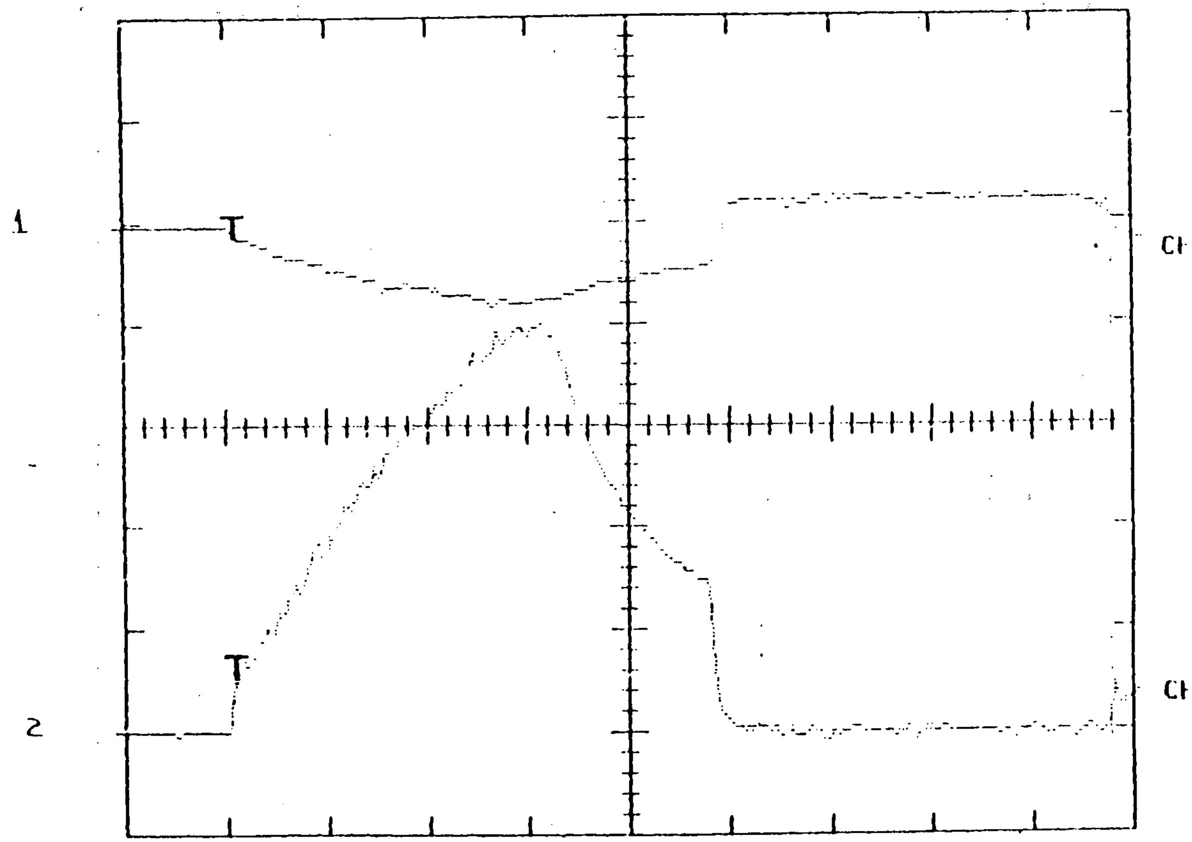
MARSHALL SPACE FLIGHT CENTER

Electromechanical Actuator Electronic Controller

NAME **Justino Montenegro** DATE **September 29, 1992**



ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
EB24	***Electromechanical Actuator Electronic Controller***	***Justino Montenegro***
CHART NO.		DATE ***September 29, 1992***



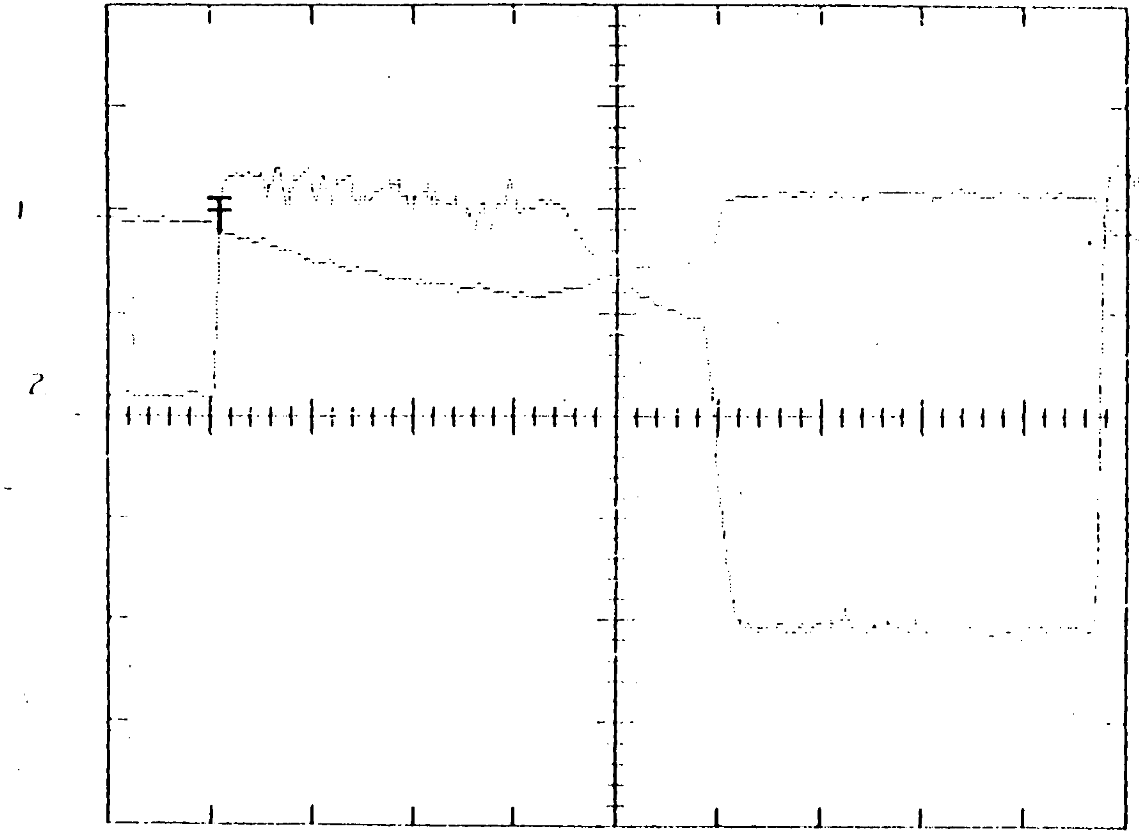
50MS/DIV

POWER INVERTER VOLTAGE PROFILE AND BATTERY CURRENT REQUIRED TO ACCELERATE MOTOR WHEN ACTUATOR COMMANDED TO EXECUTE A 0.5 IN STEP.

TRACE 1: INVERTER INPUT VOLTAGE (20V/DIV)

TRACE 2: BATTERY OUTPUT CURRENT (20A/DIV) @ 240 VDC

ORGANIZATION EB24 CHART NO.	MARSHALL SPACE FLIGHT CENTER **Electromechanical Actuator Electronic Controller**	NAME Justino Montenegro DATE September 29, 1992



50MS/DIV

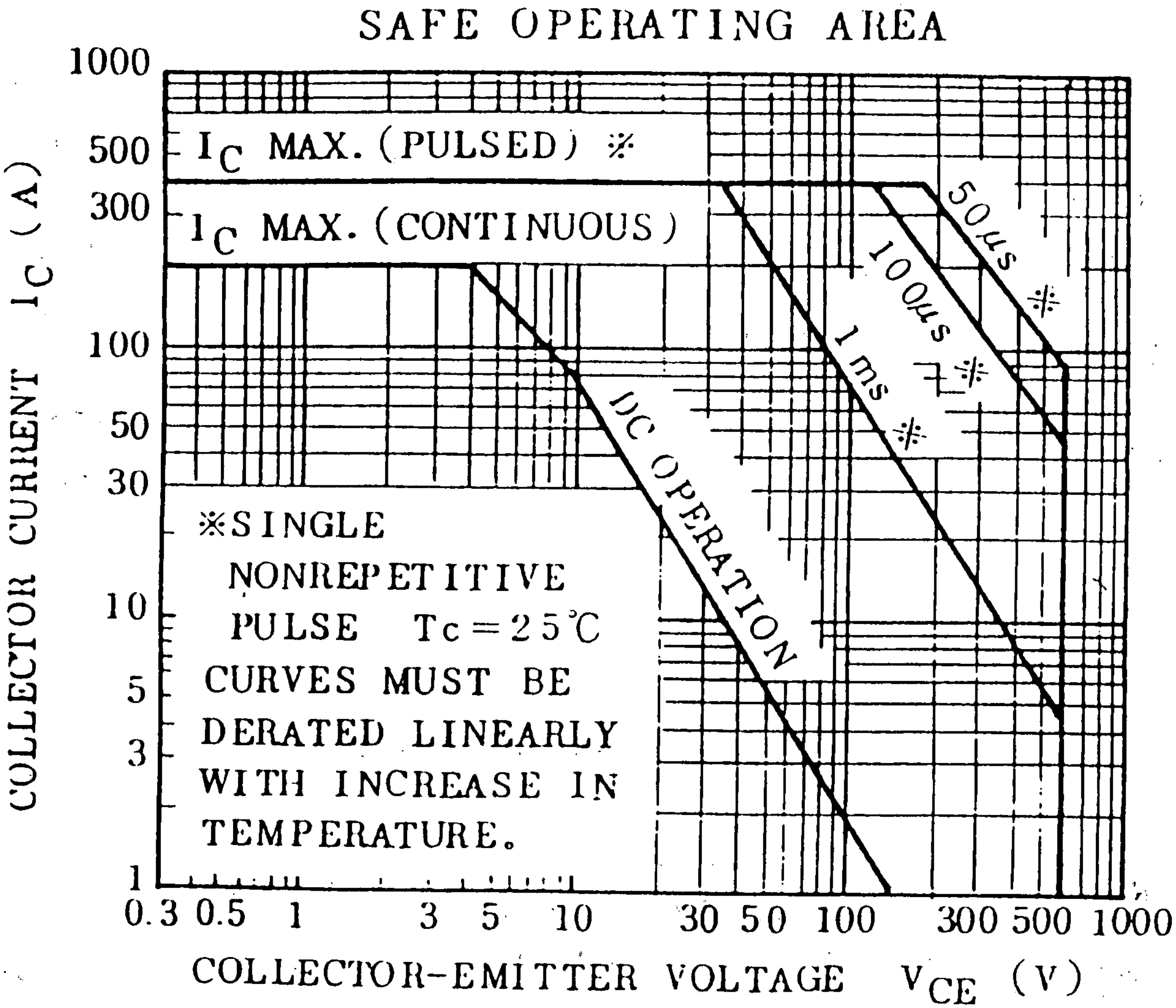
POWER INVERTER VOLTAGE PROFILE AND ACTUATOR MOTOR CURRENT WHEN ACTUATOR COMMANDED TO EXECUTE A 0.5 IN STEP.

TRACE 1: INVERTER INPUT VOLTAGE (20V/DIV)

TRACE 2: MOTOR CURRENT (50A/DIV)

BATTERY VOLTAGE: 240VDC

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
EB24	***Electromechanical Actuator Electronic Controller***	***Justino Montenegro***
CHART NO		DATE ***September 29, 1992***



ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
EB24	***Electromechanical Actuator***	***Justino Montenegro***
CHART NO.	***Electronic Controller***	DATE
		September 29, 1992

TRANSISTOR LOSS AND EMI

CONDUCTION LOSS
AT 100 AMPS

2.5 VOLTS X 100
AMPS
250 WATTS

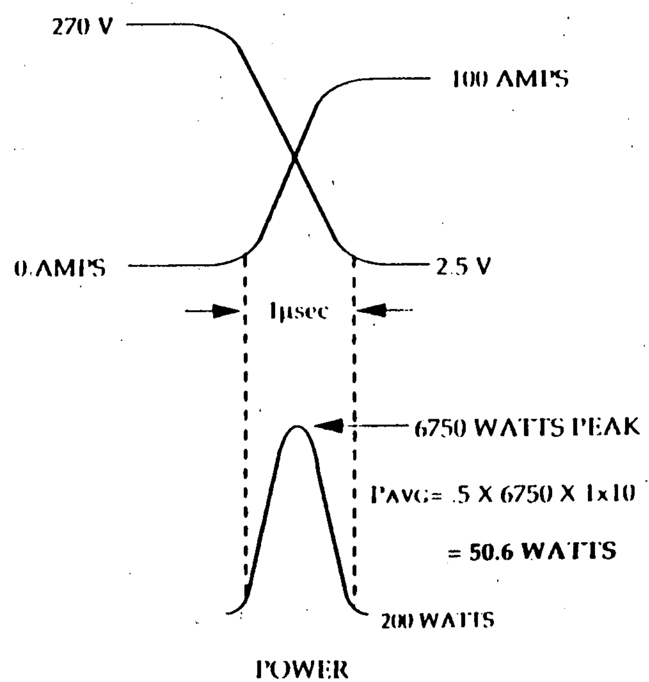
TOTAL LOSS
250 + 51
= 301 WATTS PEAK

TRANSISTOR
RATING
200 AMP CONT., 400
PEAK
600 VOLT
800 WATTS

400 AMP, 600 VOLT,
1400 WATT
UNITS AVAILABLE

AVAILABLE THIS
SUMMER
600 AMP, 600 VOLT
UNITS

SWITCHING LOSS
AT 100 AMPS
270 VOLTS, 15 KHZ



P_{AVG} = .5 X 6750 X 1×10^{-6} X 15×10^{3}

= 50.6 WATTS

EMI

DEDICATED POWER
SOURCE

MOTOR/CONTROLLER
IN CLOSE PROXIMITY

MOTOR/CONTROLLER
TOTALLY ENCLOSED

SHIELDED CABLE

RESONANT POWER CONVERSION

and

INDUCTION MOTOR CONTROL

Ken Schreiner

General Dynamics
Space Systems Division

Resonant Power Conversion Advantages vs. PWM

- Lower component stresses and improved efficiency with zero voltage or zero current switching
- Increased switching frequency to control high frequency, low inertia motors
- Lower noise and EMI
- Decreased thermal loads
- Decreased battery capacity requirements

There are Two Resonant Converter Options

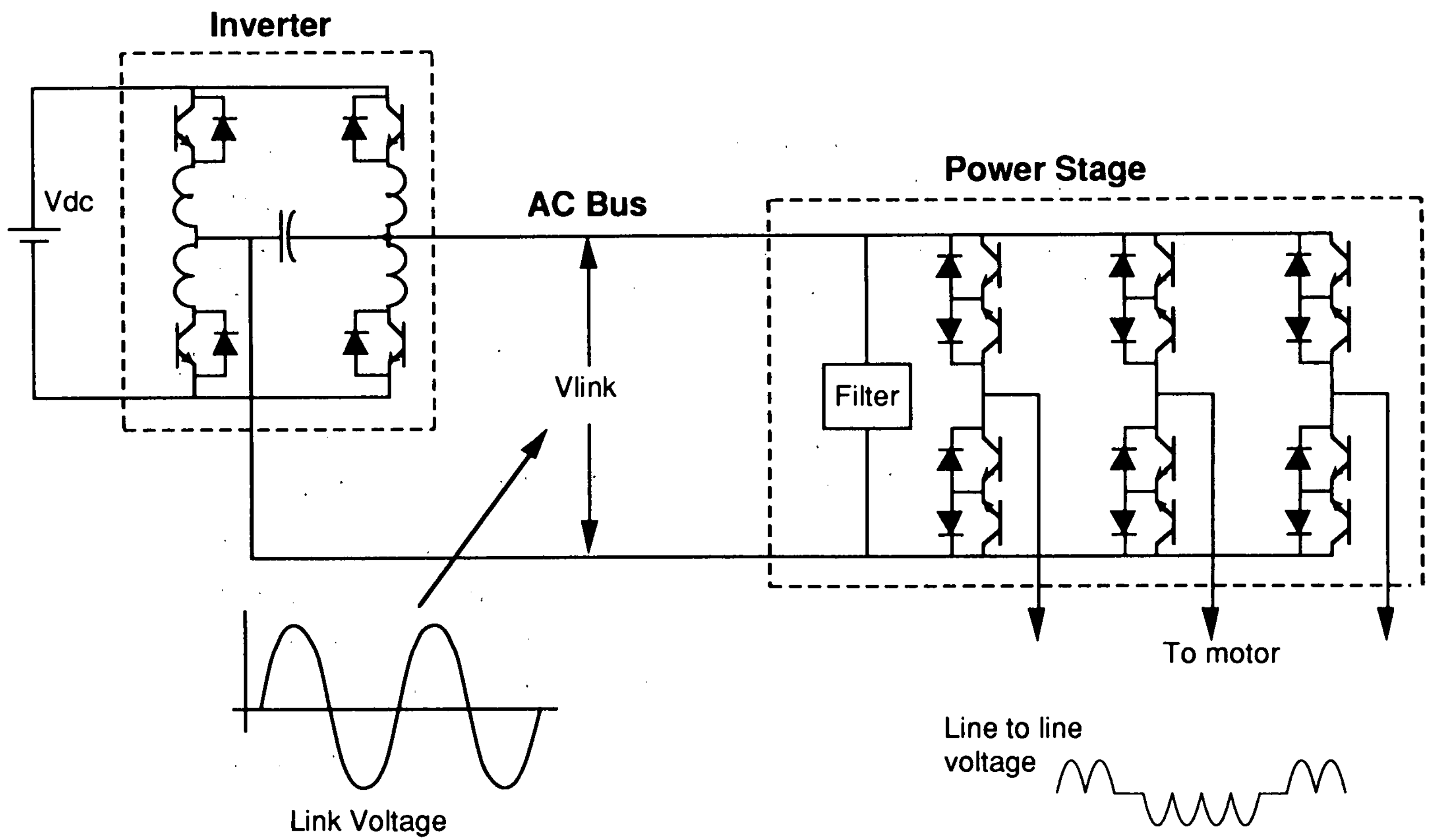
High-frequency AC resonant distribution

- Uses zero current switching resonant inverter to generate high frequency bus
- Motor controller 'steers' AC half-sine pulses to low frequency output
- Advantages where redundancy required and high fault currents may need to be interrupted

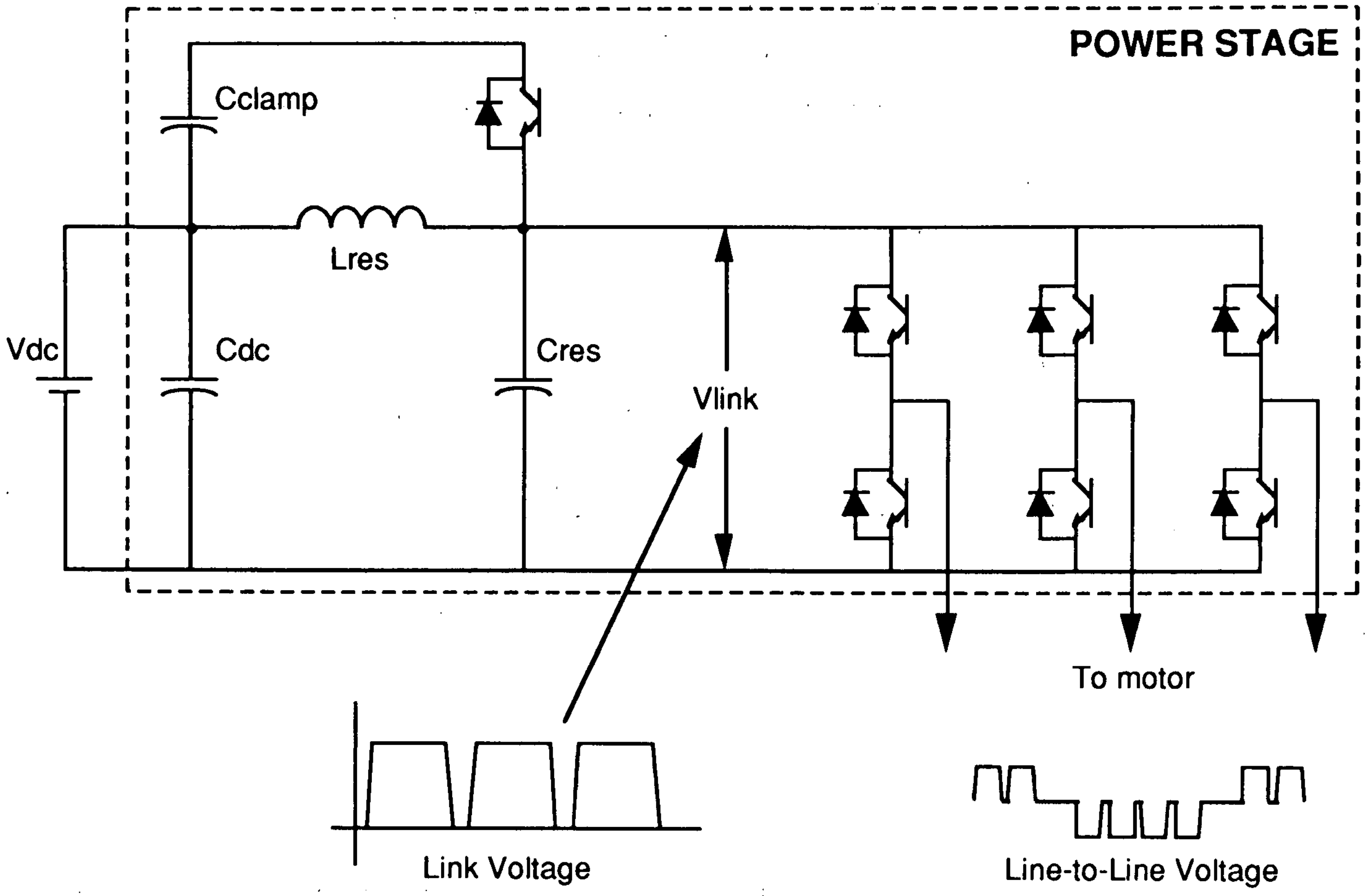
Resonant DC converter

- Adds an inductor and capacitor to the normal six switch bridge to perform resonant zero voltage switching
- Advantages where high efficiency and high power required in dedicated configuration

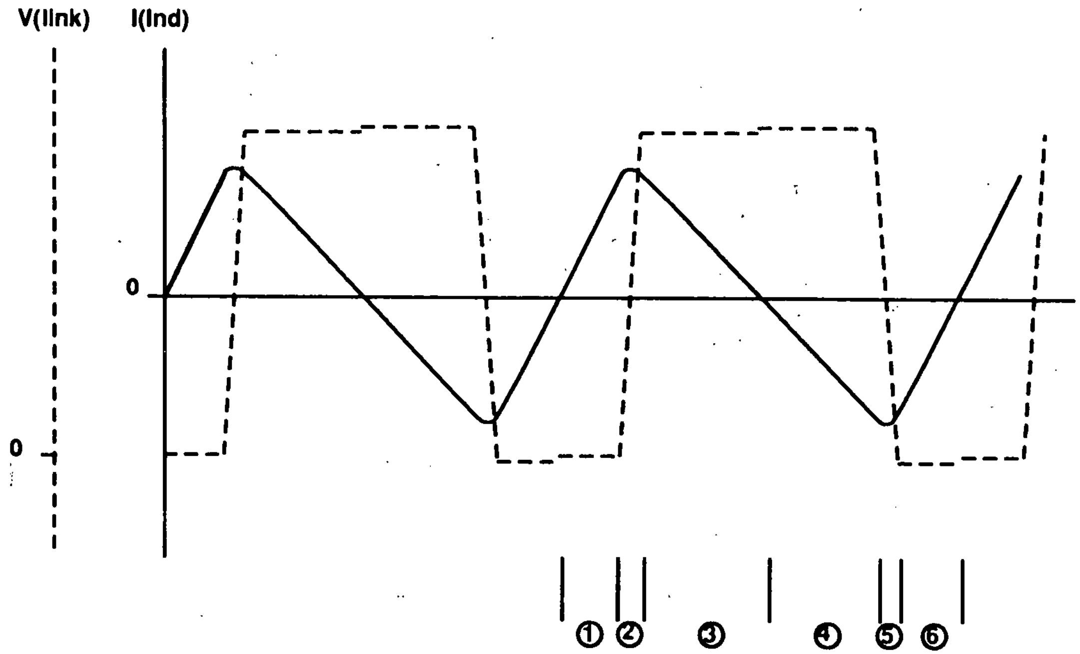
AC Resonant Topology



DC Resonant Topology



DC Resonant Link Operation



① Bridge switches conduct - build up inductor current

②⑤ Resonant rise/fall of link voltage

③ Clamp diode conducts - turn on clamp switch

④ Clamp switch conducts

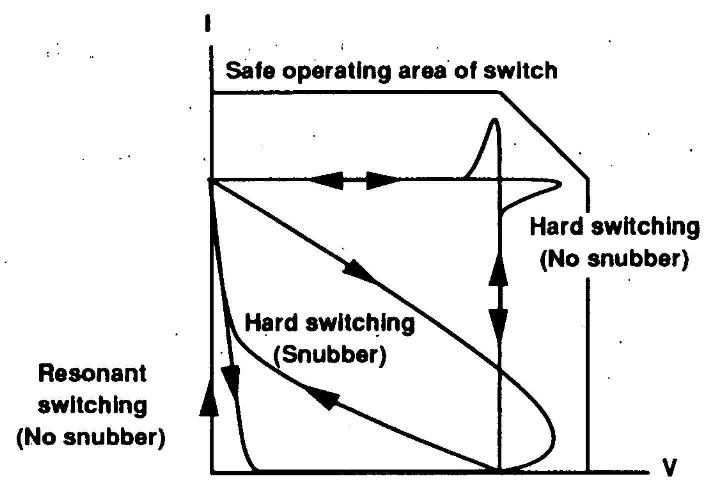
⑥ Bridge diodes conduct - turn on bridge switches

The Resonant DC LinkConverter Has

- Higher overall efficiency than PWM or AC Resonant Topologies
- Fewer Switches and Reactive Components Than AC Resonant
- No–Load Switch Losses are Light
- ALS Will be Using a Single–String Actuator Topology
- Easy to Synchronize Zero Voltage Switching

Resonant switching is superior to hard switching

- Better switch utilization
- Lower losses
- Lower device stresses

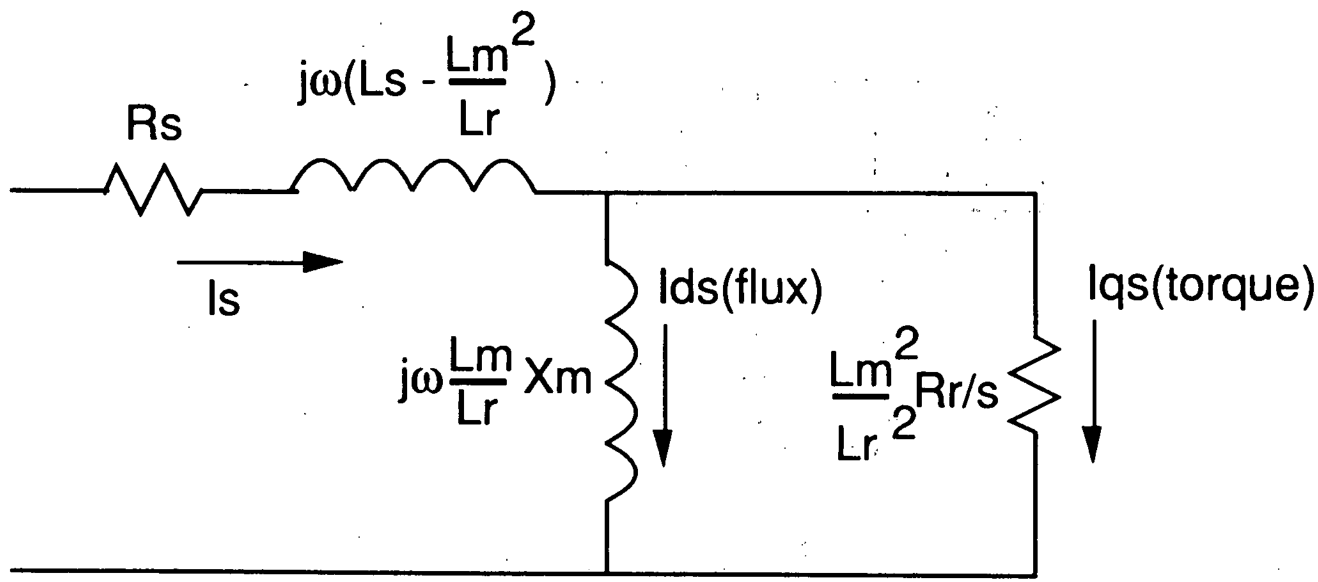


Induction Motor Control

Why Induction Machines?

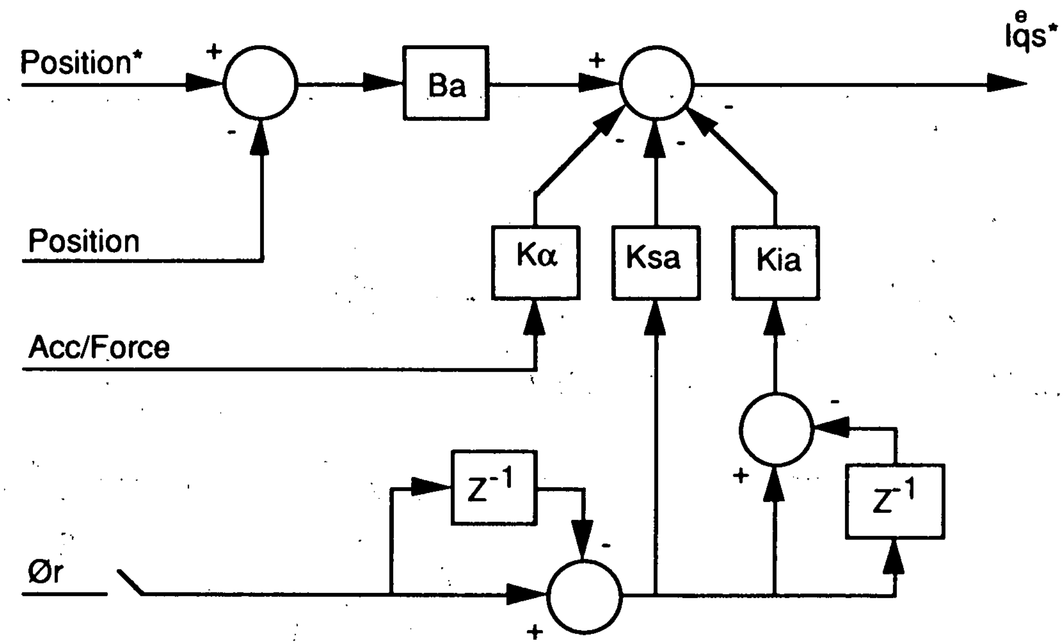
- Motor is rugged
- Motor temperature limited by insulation rating only
- Field extinguished by reducing motor voltage
- Motor losses comparable to dc motor losses

Induction Machine Control Concepts



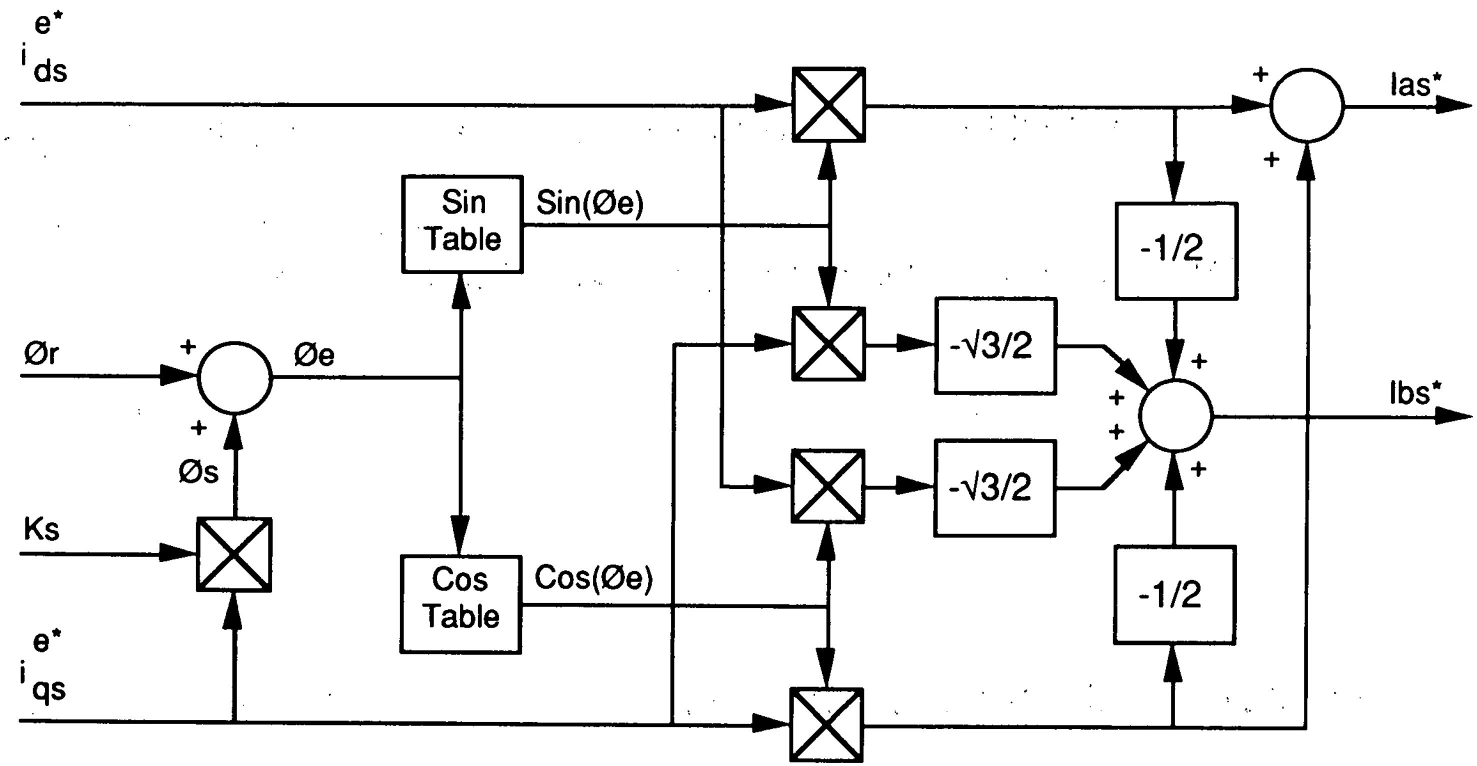
$$T = \frac{3 \cdot p \cdot Lm \cdot \lambda^e dr}{4 \cdot Lr} \cdot Iqs = Kt \cdot Iqs \qquad \omega s = \frac{Rr \cdot Lm \cdot Iqs}{Lr \cdot \lambda^e dr} = Ks \cdot Iqs$$

State Variable Position Controller



- Generates motor torque command

Current 2 to 3 Axis Frame Transformation

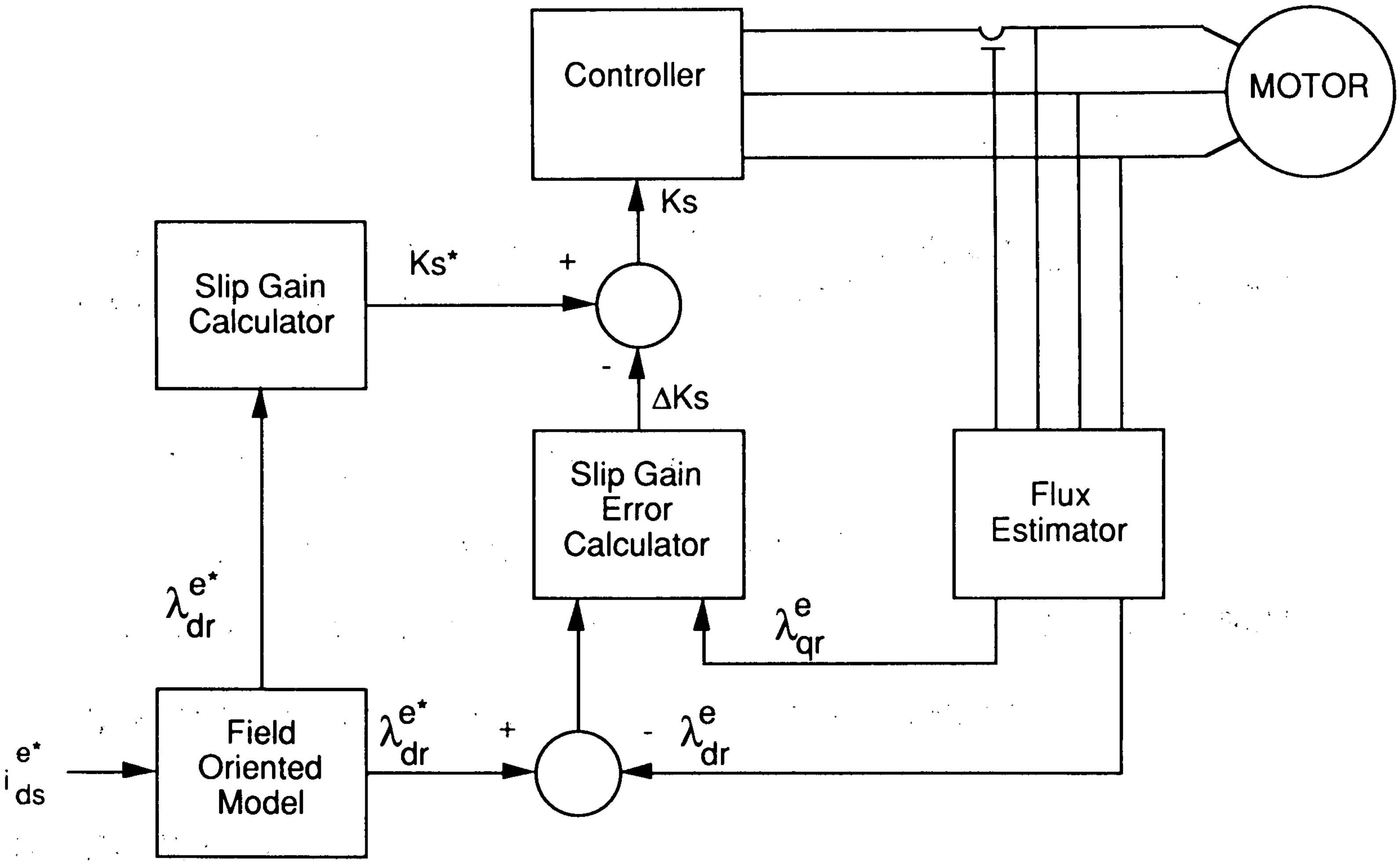


- **Transforms dc torque and flux currents to three phase current commands**

Machine Parameter Sensitivity

- Proper motor control requires knowing the following parameters:
  - Lm
  - Lr
  - Rr
- Lm and Lr are a function of flux level and can be obtained from lookup tables
- Rr can be determined from measurements of rotor flux

Slip Gain Controller Implementation



- **Maintains proper vector orientation of the induction machine**

SUMMARY

Use of Emerging Technologies has Resulted in:

- Power converters with reduced losses and increased reliability
- Induction machines that are rugged and efficient
- Increased controller performance

Construction of the full scale controller is nearing completion with design verification early next year at MOOG.

ELECTRIC THRUST VECTOR CONTROL FOR NATIONAL LAUNCH SYSTEM (NLS)

SEPTEMBER 28, 1992

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER

AGENDA

- ALLIED-SIGNAL AEROSPACE COMPANY
- ELECTRIC ACTUATION NEEDS
- POWER SOURCE/ACTUATION CAPABILITIES
- ELECTRIC ACTUATION SYSTEM SOLUTIONS
- SUMMARY/RECOMMENDATIONS

1991 SALES:
$11.8 BILLION
98,000 EMPLOYEES

Allied Signal

AN ADVANCED TECHNOLOGY COMPANY WITH PRIMARY BUSINESSES IN AEROSPACE/ ELECTRONICS, AUTOMOTIVE, AND ENGINEERED MATERIALS

RESEARCH CENTER

ALLIED-SIGNAL AEROSPACE CO.

- AIRESEARCH
- BENDIX
- BENDIX/KING
- GARRETT

$5.3 BILLION

AUTOMOTIVE SECTOR

- AUTOLITE/FRAM
  - SPARK PLUGS/FILTERS
- BENDIX GROUP
  - FRICTION MATERIALS
  - BRAKE SYSTEMS
  - SAFETY RESTRAINTS
- GARRETT GROUP
  - TURBOCHARGERS
  - INTERCOOLERS

$4.1 BILLION

ENGINEERED MATERIALS SECTOR

- UOP PROCESS DIVISION
- NORPLEX/OAK DIVISION
- FLUORINE PRODUCTS DIV.
- PLASTICS AND PERFORMANCE MATERIALS
- FIBERS DIVISION

$2.4 BILLION

IG-03291-1

ELECTRICAL ACTUATION NEEDS

HOW TO SIGNIFICANTLY REDUCE COST OF FUTURE SPACE FLIGHT

- IMPLEMENTATION OF FAULT TOLERANT
- OPERATION IN PRESENCE OF FAULTS (FAULT MASKING)
- BUILT-IN-SYSTEM/COMPONENT TEST

IW-19379

POWER SOURCE/ACTUATOR CAPABILITIES

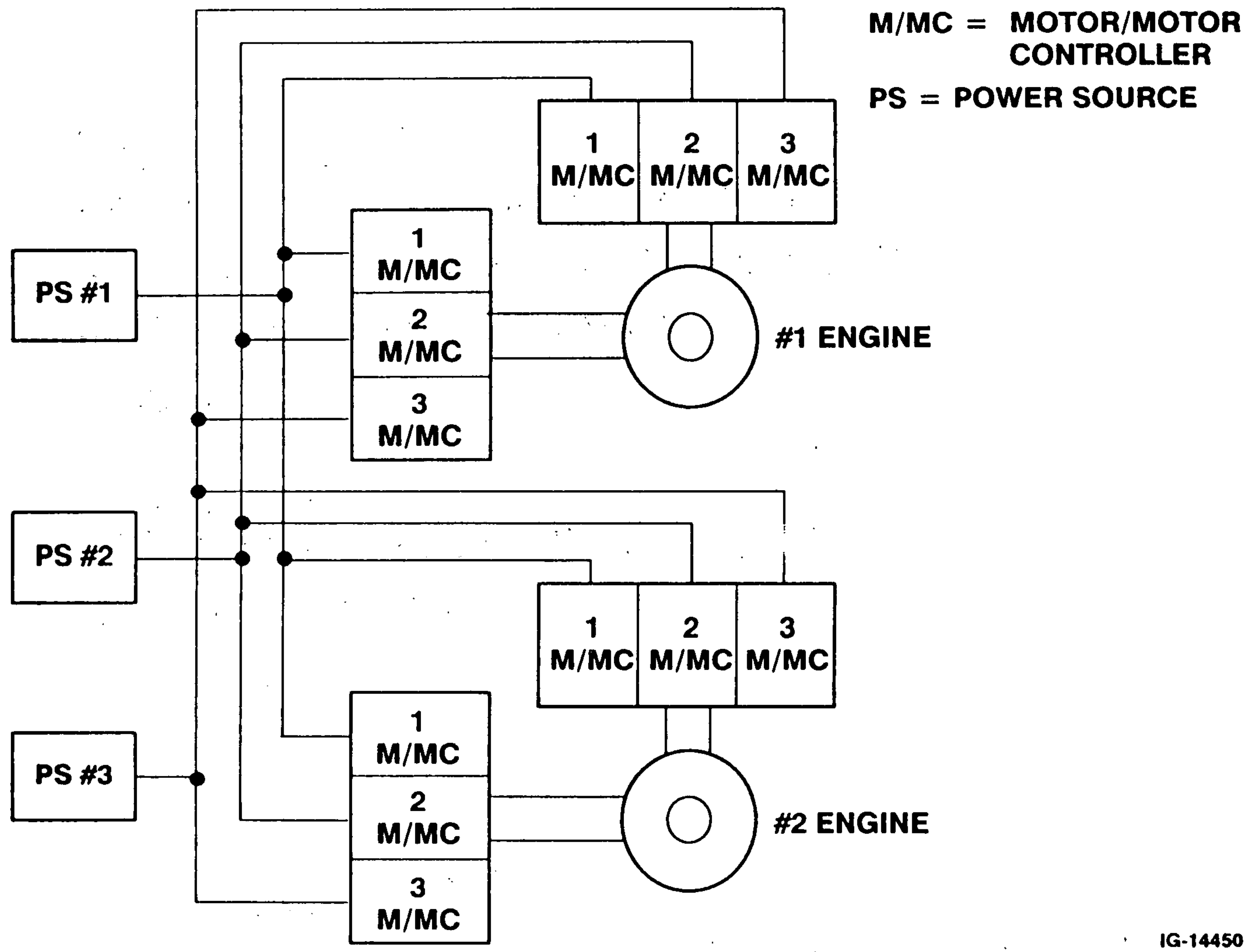
IW-18000

WHAT DOES FAULT TOLERANCE IMPOSE ON SUCH SYSTEMS AS TVC

- POWER SOURCE
  - MULTIBUS DISTRIBUTION
  - FAILURE OF SINGLE BUS DOES NOT IMPACT PERFORMANCE
- ACTUATION
  - MULTI CHANNEL APPROACH
  - FIRST CHANNEL FAILURE TRANSPARENT
  - SECOND CHANNEL FAILURE RESULTS IN SAFE (NULL) SYSTEM

IW-19380

3 CHANNEL FAULT TOLERANCE TWO ENGINE T.V.C. SYSTEM

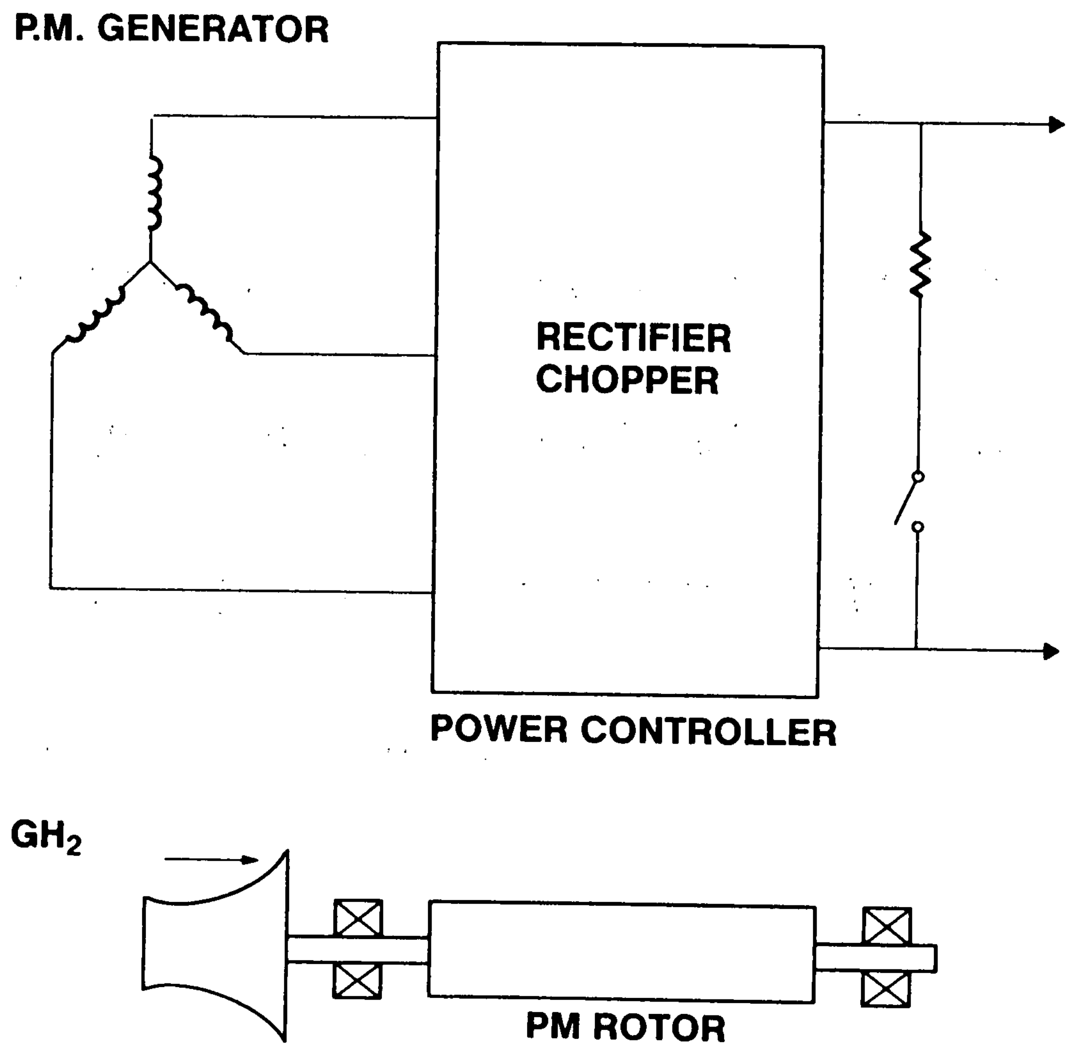


IG-14450

WHAT ARE POWER SOURCE REQUIREMENTS

- BIDIRECTIONAL POWER BUS
- TIGHT VOLTAGE REGULATION (MIN. LOAD KVA)
- PROVIDE DISSIPATION/STORAGE FOR REGENERATED POWER
- FULLY TESTABLE WITH ONLY ELECTRICAL POWER SUPPLIED

POSSIBLE SOLUTION – GH_2 TURBOALTERNATOR/ POWER CONDITIONER

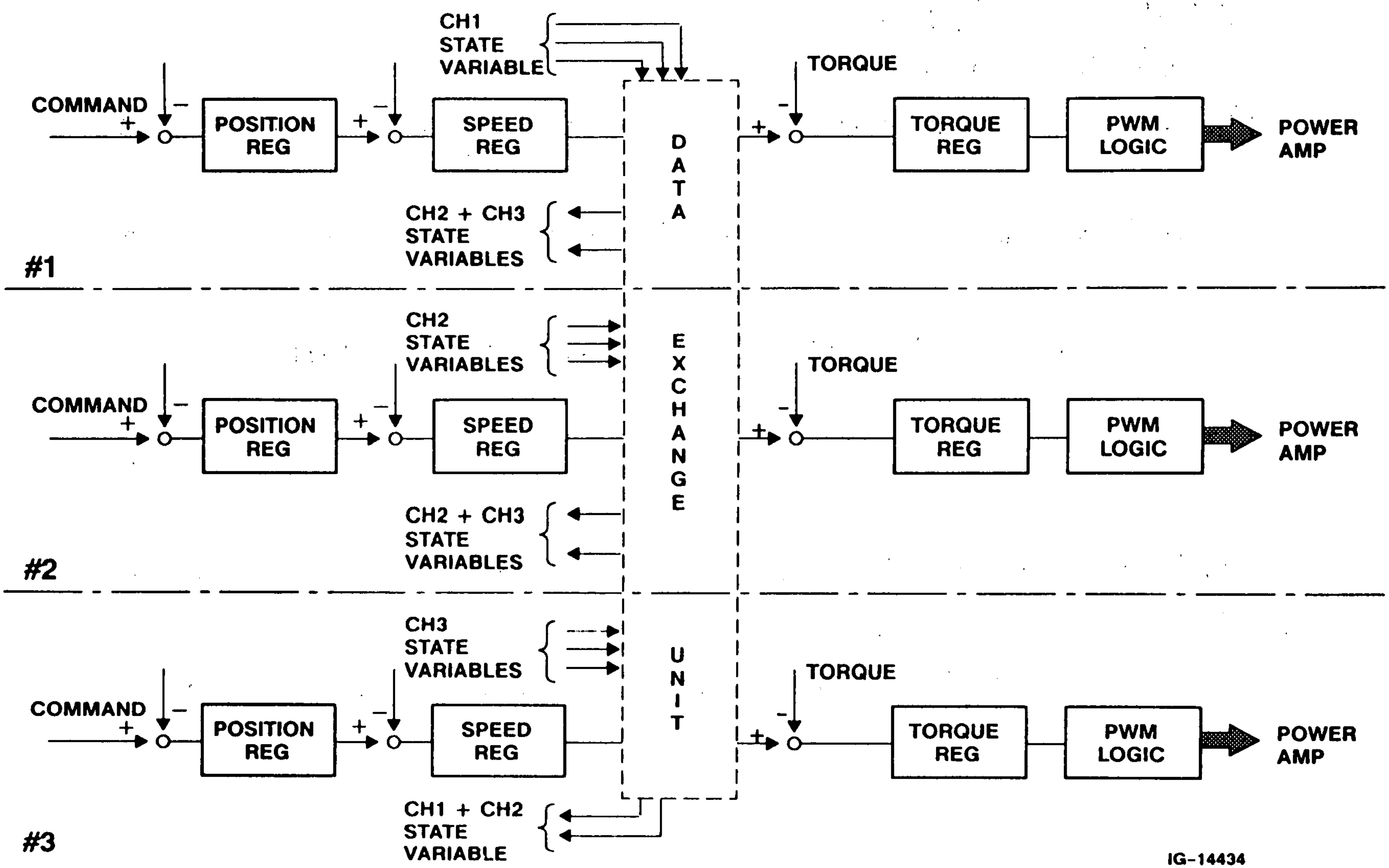


IG-14424

WHAT ARE ACTUATOR REQUIREMENTS?

- FULLY TESTABLE WITH ELECTRICAL POWER
- FULL REGENERATIVE CAPABILITY (MINIMIZES HEAT LOAD)
- HIGH EFFICIENCY
- FIRST FAULT TRANSPARENT (REPORTED) TO VEHICLE
- SECOND FAULT CAUSES SAFE (NULL) OF ACTUATION
- FREQUENCY RESPONSE
  - TORQUE LOOP > 1000 HZ
  - SPEED LOOP > 50 HZ
  - POSITION LOOP > 10 HZ

BLOCK DIAGRAM FOR MULTICHANNEL FAULT TOLERANT SYSTEM



HOW IS REDUNDANCY IMPLEMENTED?

- ALL CHANNELS ARE SYNCHRONIZED WITH RESPECT TO COMPUTATIONAL FRAME
- DATA IS EXCHANGED BETWEEN CHANNELS AT FRAME RATE SO THAT LOCAL CHANNEL HAS GLOBAL DATA
- LOCAL CHANNEL USES IDENTICAL GLOBAL DATA TO COMPUTE SPEED AND TORQUE COMMANDS
- LOCAL SPEED/TORQUE TRANSMITTED GLOBALLY
- TORQUE COMMANDS ARE IDENTICAL, AND THIS USED TO BALANCE MULTI CHANNEL ACTUATOR

HOW IS REDUNDANCY IMPLEMENTED? (CONT'D)

- GLOBAL DATA IS VOTED AT "VOTING PLANE" THAT HAS ABILITY TO ELIMINATE FAULTY DATA BUT MAINTAIN CHANNEL INTEGRITY
- FOR TVC – VOTING PLANE IS AT TORQUE CMD
- IF NON IDENTICAL COMPUTED GLOBAL DATA, FAULTY COMPUTATION IS REJECTED
- IF SENSED STATE VARIABLE DIFFER BY > "ϵ", FEEDBACK IS ELIMINATED
- IF FAILURE CLEARS ITSELF – (P/S FAILURES) RESYNCHRONIZATION OF CHANNEL IS AUTOMATIC

IW-19400-1

HOW IS HEALTH MANAGEMENT ACCOMPLISHED

- EACH CHANNEL HAS GLOBAL DATA AND LOCAL DATA AVAILABLE
- COMPARISON OF DATA ENABLES COMPLETE CHANNEL HEALTH EVALUATION BASED UPON GLOBAL AND LOCAL DATA
- HEALTH MAINTAINENCE RESIDES AT SUBSYSTEM LEVEL AND IS NOT PASSED "UP THE LINE"

WHAT DOES THIS IMPOSE UPON ACTUATOR DEVICES

- MULTI-CHANNEL APPROACH
- ALL CHANNELS EQUALLY SHARE LOAD
- EACH CHANNEL IS RATED $\left(\frac{1}{N-1}\right)$ SYSTEM REQUIREMENTS
- FAULT TOLERANT ARCHITECTURE BE UTILIZED

FROM SYSTEM PERSPECTIVE – WHAT IS IMPACT ON PEAK POWER UTILIZING 3 CHANNELS

- CONSIDER ALL MOTORS ARE DESIGNED WITH CONSTANT L/D PARAMETERS. FOR SINGLE MOTOR TO PERFORM TASK L_I, D_I

$$\text{TORQUE} = K_1 D^2 L$$

$$\text{INERTIA} = K_2 D^4 L$$

$$\frac{\text{TORQUE}}{\text{INERTIA}} \; a \; \frac{1}{D^2}$$

FOR A 3 MOTOR SYSTEM, EACH MOTOR RATED 1/2 OF SINGLE MOTOR

$$\text{TORQUE}/_{3\ \text{MOTOR}} = 1/2\ \text{TORQUE}/_{1\ \text{MOTOR}} = 1/2\ K_1 D_1^2 L_1$$
$$= K_1 D_2^2 L_2$$

IW-19384

WHAT IS IMPACT ON PEAK POWER – (CONT'D)

$$\text{TORQUE}/_{3\ \text{MOTOR}} = K_1 D_2^2 L_2 = 1/2\ K_1 D_1^2 L_1$$

$$\frac{L}{D} \text{ IS CONSTANT, } \frac{L_1}{D1} = \frac{L_2}{D2}$$

$$\therefore\ D_2 = D_1 (1/2)^{1/3}$$

$$\frac{\left.\frac{\tau}{I}\right|_{1\ \text{MOTOR}}}{\left.\frac{\tau}{I}\right|_{3\ \text{MOTOR}}} = \frac{\frac{K_1}{K_2 D_1^2}}{\frac{K_1}{K_2 D_1^2}} = (1/2)^{2/3}$$

$$= 0.63$$

i.e., POWER TO ACCELERATE MOTOR INERTIA IS REDUCED BY 37% FOR SINGLE MOTOR CONFIGURATION

IW-19385

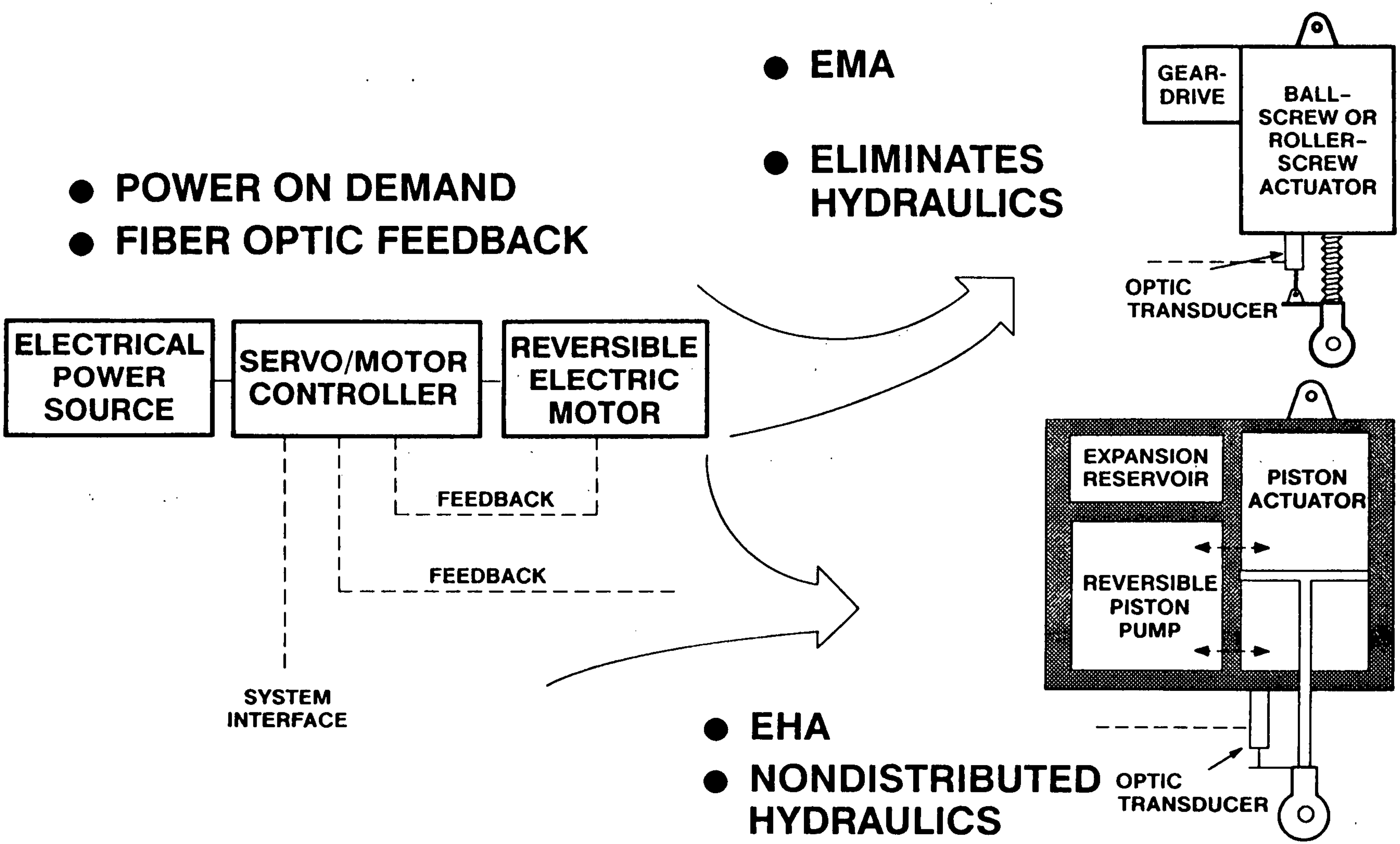
ELECTRICAL ACTUATION SYSTEM SOLUTIONS

ALAD/BOEING PROVIDES STATE-OF-THE-ART ELECTRICAL ACTUATION SUBSYSTEMS

- POWER ON DEMAND
- FIBER OPTIC FEEDBACK

- EMA
- ELIMINATES HYDRAULICS

- EHA
- NONDISTRIBUTED HYDRAULICS



IG-09445

WHAT ARE POSSIBLE T.V.C. SYSTEM SOLUTIONS?

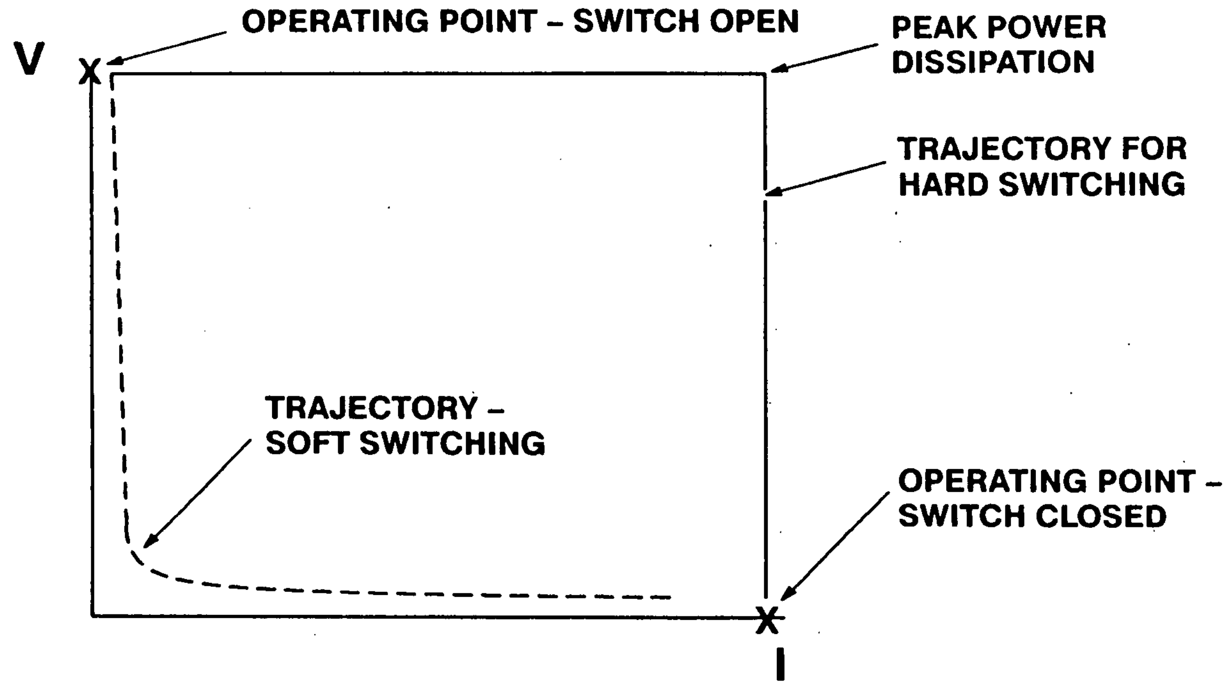
ACTUATOR:	ELECTROMECHANICAL
	ELECTROHYDRAULIC
MOTOR:	PERMANENT MAGNET
	INDUCTION
	SWITCHED RELUCTANCE
INVERTER:	HARD SWITCH
	SOFT SWITCH
CONTROL:	PULSE WIDTH MODULATION
	PULSE DENSITY MODULATION

IW-19387

HOW TO EVALUATE THE DIFFERENT MOTORS

	INDUCTION	PM	S/R	IMPACT	SIG-TVC
TORQUE/INERTIA	HIGH	HIGH	LOW	POWER SOURCE	HIGH
POWER FACTOR	0.6 – 0.7	0.8 – 1	?	CONTROLLER KVA SYSTEM WT.	HIGH
TORQUE PULSATIONS	NONE	NONE	HIGH	CONTROL LOOP	HIGH
EFFICIENCY	GOOD	BETTER	GOOD	THERMAL DESIGN SYSTEM WT.	HIGH
SENSORS	SPEED	ROTOR POS SPEED	ROTOR POS SPEED	RELIABILITY	LOW
VARIABLE FLUX	YES	NO	YES	NONE	LOW
SELF EXCITATION	NO	YES	NO	ACTUATOR DESIGN UNDER FAULT	HIGH
HIGH TEMP. ROTOR	YES	NO	YES	ACTUATOR TEMP <200°C	LOW

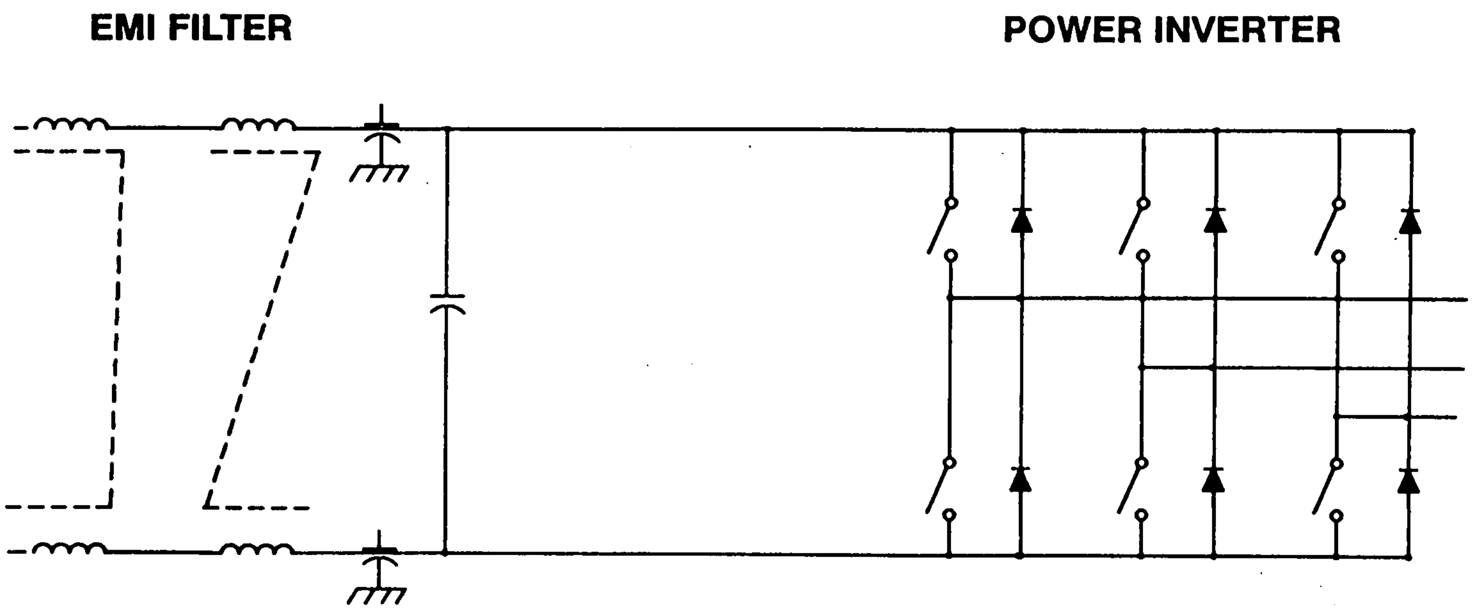
HARD SWITCHING VS. SOFT SWITCHING



- SWITCHING LOSSES ARE ELIMINATED WHEN SOFT SWITCHING IS INCORPORATED
- RESONANT CIRCUIT MUST OPERATE – CONTINUOUSLY – AND HAS LOSSES ASSOCIATED WITH IT

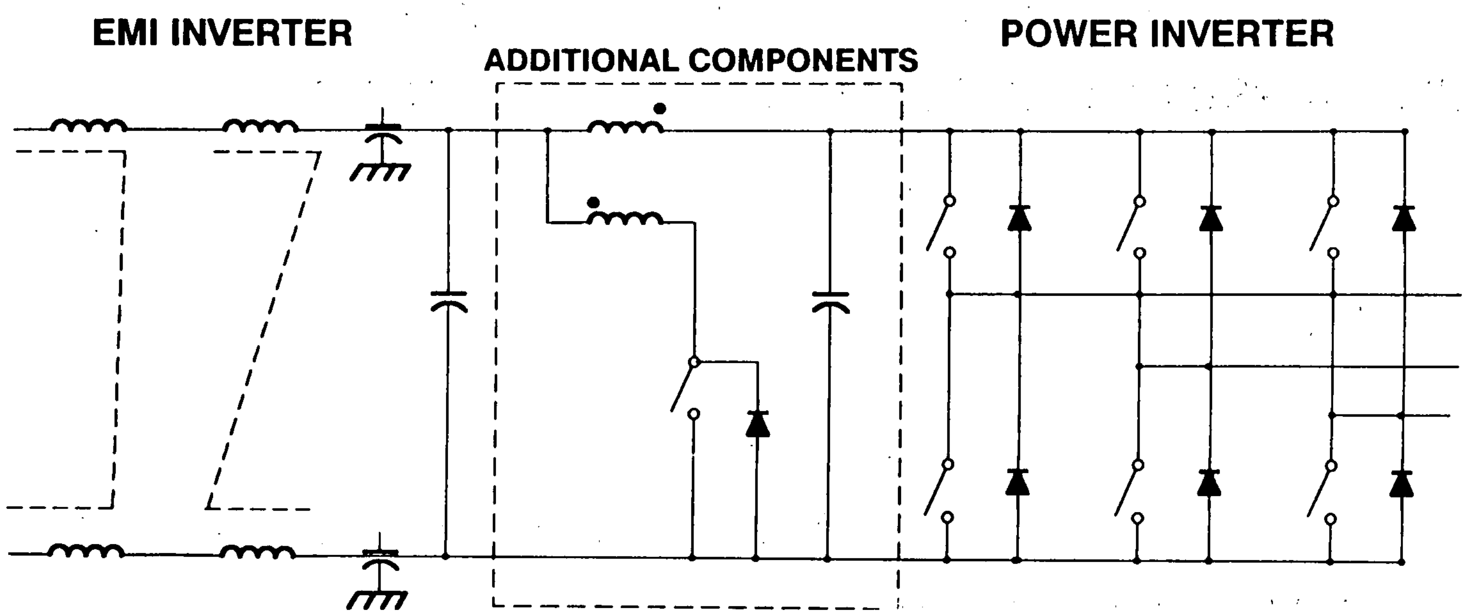
IG-14425

HARD SWITCHING INVERTER SCHEMATIC



IG-14426

SOFT SWITCHING INVERTER SCHEMATIC

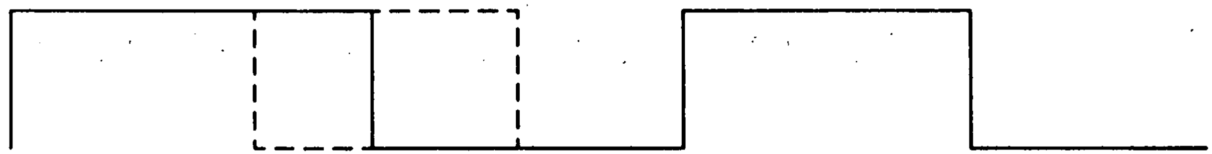


- ADDED PARTS INCREASE COST, WEIGHT, REDUCE RELIABILITY

IG-14427

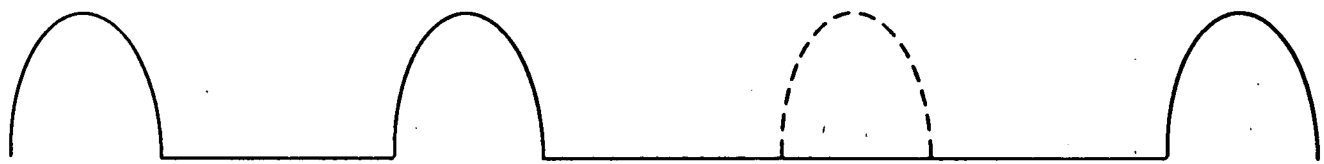
PULSE WIDTH COMPARED TO PULSE DENSITY MODULATION

PWM



- AVERAGE VALUE OF OUTPUT IS INFINTELY ADJUSTABLE
- CONTROLLABILITY IS EXCELLENT
- FREQUENCY LIMITED TO 20 – 50 KHZ

PDM



- AVERAGE VALUE OF OUTPUT CONTROLLED BY MISSING PULSES
- ADEQUATE CONTROLABILITY AT HIGH FREQUENCY
- FREQUENCY > 50 KHZ

IG-14428

HOW TO EVALUATE THE DIFFERENT CONTROL OPTIONS

	PDM	PWM	IMPACT	SIGNIFICANCE
MOTOR EMI	LOW	HIGH	NONE	LOW
SUPPLY EMI	HIGH	LOW	SUBHARMONIC FREQUENCIES EMI FILTER	HIGH
OPERATING FREQ.	>50 KHZ	> 20 KHZ	LOAD RIPPLE	LOW
LEAKAGE DISPLACE-MENT CURRENTS	LOWER dv/db	HIGHER dv/db	FILTER WEIGHT (COMMON MODE)	LOW
FAULT TOLERANCE	LOW	HIGH	S.E.E. BECOME BURN OUT	HIGH
DEVICE RATING	>1.5 PU VOLTAGE + CURRENT	1 PU	COST, SIZE	HIGH
LOOP FREQUENCY RESPONSE	APPROX. 200 HZ	>2000 HZ	CONTROLLABILITY	HIGH

Allied-Signal Aerospace Company

AiResearch Los Angeles Division IW-19389

Allied Signal

WHAT ARE RECOMMENDATIONS FOR TVC

- PWM/PM MOTORS ARE MATURE SYSTEM
- ANY POWER LEVEL REQUIRED FOR TVC IS ACHIEVABLE WITH TODAYS TECHNOLOGY
- TECHNOLOGY IS DEVELOPED AND WELL UNDERSTOOD
- PWM/PM PROVIDES ROBUST SYSTEM
- ALL ADVANCES IN POWER AND CONTROL ELECTRONICS WILL EQUALLY HELP PWM/PDM
- WHERE TEMPERATURES $<200\,^\circ C$ ARE ENCOUNTERED, PWM, PM IS THE PREFERRED SYSTEM
- FOR TEMPERATURES $>200\,^\circ C$ – INDUCTION MOTORS/PWM BECOMES PREFERRED SYSTEM

IW-19390

Honeywell

TITAN IV STAGE 1 BOOSTER TVC PERFORMANCE PREDICTIONS FOR ELECTROMECHANICAL ACTUATORS

Jeff Ring

Advanced Programs

(813) 539 - 5672

TITAN IV TVC STAGE 1 BOOSTER EMA PERFORMANCE STUDY

Honeywell

- Specified Performance Requirements
  (Cylinder Assembly, Actuating, Linear - Booster Engine Control, PD4600008)
  - Stroke = ± 1" , Figure 11
  - No Load Velocity Limit = 3.5 in/sec, Para. 3.1.1.14.3
  - Loaded Velocity Limit = 2.5 to 3.5 in/sec, Para. 3.1.1.14.3
  - Output Load Capability = 30000 lb, Para. 3.1.1.2
  - Closed Loop Bandwidtn = 8 hz, Table 1
- Specified Load Parameters
  - Engine Inertia = 518 slug - ft^2, Para. 3.1.1.20
  - Engine Natural Frequency = 13.5 hz, Para. 3.1.1.20
  - Engine Moment Arm = 14.34 in, Para. 3.1.1.20
- Motor/Actuator Design Conducted
- Closed Loop Feedback Controller Designed
- Motor/Actuator/Load/Controller modeled and simulated
- Performance evaluation conducted

TITAN IV TVC STAGE 1 BOOSTER EMA PERFORMANCE STUDY

The procedure for evaluating EMA performance for the Titan IV stage 1 booster TVC involved several steps. The first step was to determine the performance requirements. These requirements were obtained from the Martin Marietta *Cylinder Assembly, Actuating, Linear - Booster Engine Control, PD4600008* document. The key requirements for stroke, no-load and loaded velocity limits, output load capability, and closed loop bandwidth were extracted from this document as indicated above.

The EMA is coupled to a compliant load. This load is characterized by the engine inertia, natural frequency, and moment parameters listed above. This information is used as a data base to construct a dynamic load model.

The next step was to develop a "strawman" motor/actuator design that can achieve the specified performance requirements. A math model of the strawman motor/actuator and compliant load was used to conduct a closed loop feedback control algorithm. This algorithm was incorporated into the motor/actuator/load model and a stability and performance analysis was conducted.

INTEGRATED DESIGN APPROACH IS NECESSARY

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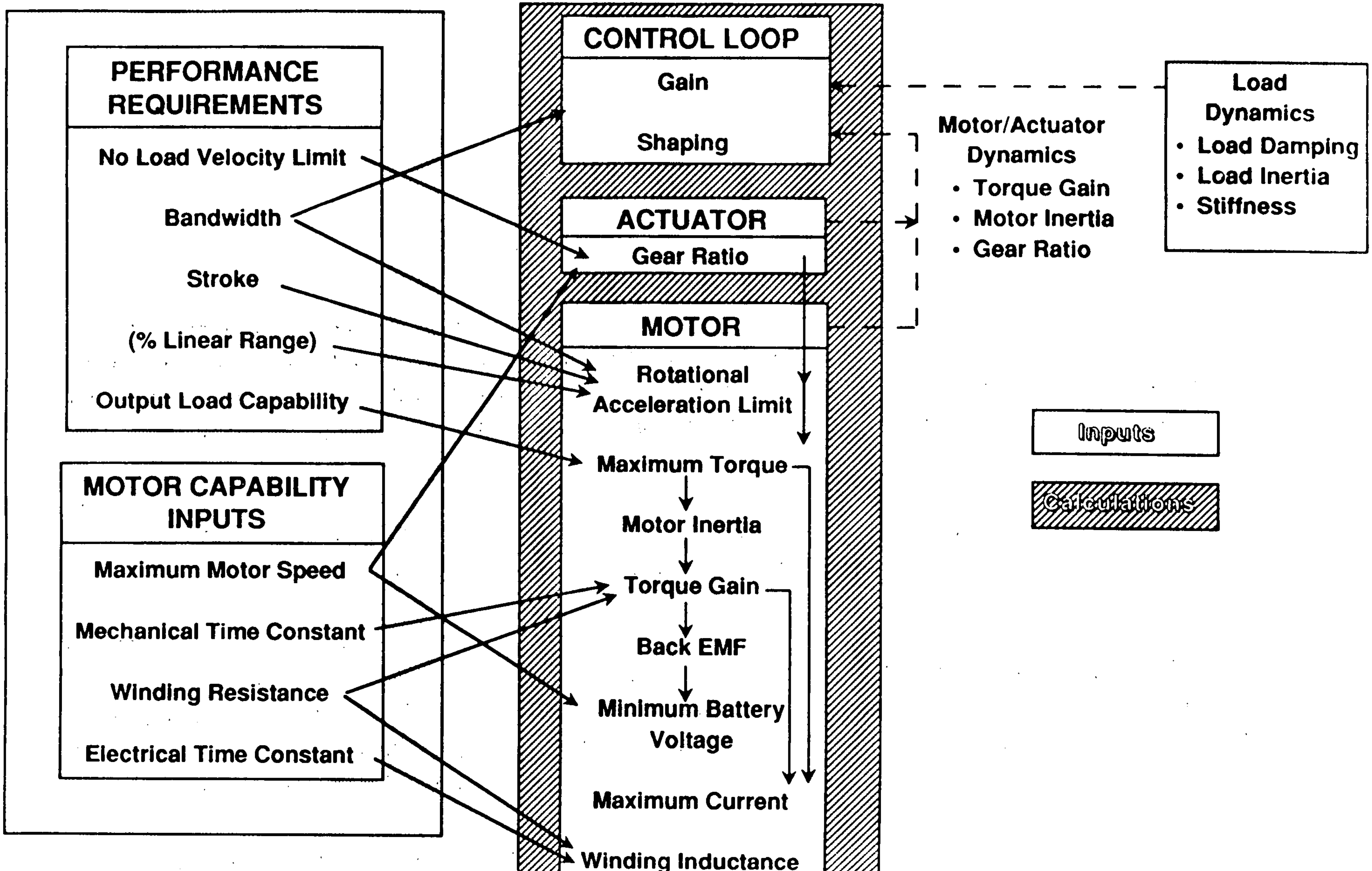

INTEGRATED DESIGN APPROACH IS NECESSARY

An integrated design approach should be followed for EMA TVC systems. This is apparent from the interrelationships which exist between the functional elements of the EMA system block diagram above. The control loop, actuator, and motor designs are dependent on the performance requirements, motor state of the art capabilities, and load coupling dynamics. Off the shelf actuation systems will not be "optimized" for performance, size, weight, power, and etc. because they have not taken fully into consideration application specific interrelationships. A custom design which utilizes an integrated design approach and comprehensive system analysis is therefor necessary when maximum performance and minimum size, weight, and power are crucial.

Summary Of Stage 1 EMA Parameters

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Parameter	Description	Value	Units
N	Roller Screw Gear Ratio	50.86	rad/in
K_A	Actuator Stiffness	100000	lb/in
K_e	Back EMF	.41	volt/rad/sec
K_m	Torque Sensitivity	.303	ft-lb/amp
J_m	Motor Inertia	5.41×10^{-3}	slug-ft^2
$V_{BATTERY}$	Battery Voltage	73	volts
I_{max}	Maximum Current	81	amps
ω_{max}	Maximum Motor Speed	1700	rpm
R	Winding Resistance	.23	ohms
L	Winding Inductance	.23	mhenries

SUMMARY OF STAGE 1 EMA PARAMETERS

A "strawman" motor/actuator design was conducted which does not violate current state of the art motor limitations and which will meet the specified Titan IV stage 1 booster TVC performance requirements. Defining EMA parameters, their description and numerical values are listed.

Load Capability And Velocity Limits Requirements Achieved

Honeywell

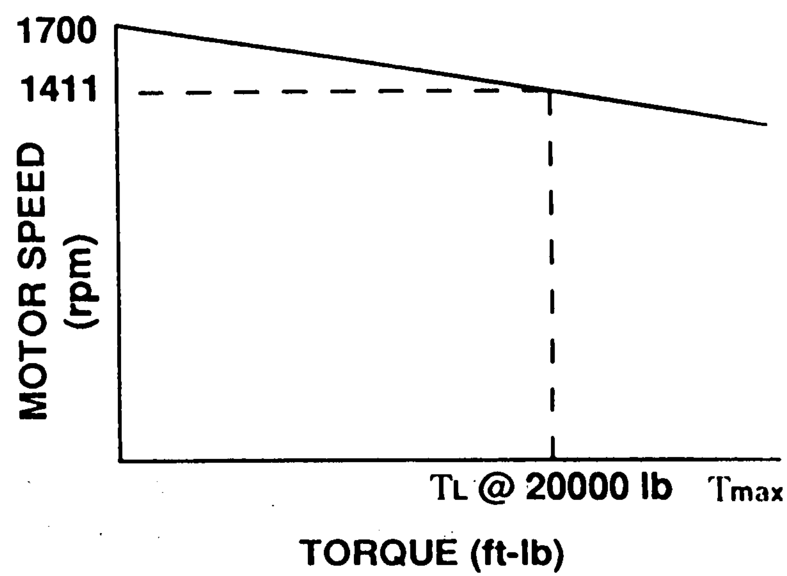
- **Output Load Capability Verification**

Stall Current	X	Torque Sensitivity	X	Gear Ratio	X	Number of Motors	=	Stall Force
81 amps		.303 ft-lb/amp		(50.86 rad/in) (12in/ft)		2		29960 lbs

- **Velocity Limits Verification**

No Load Motor speed	/	Gear Ratio	=	No Load Velocity Limit
1700 rpm $\left(\frac{2\pi}{60}\ \frac{\text{rad/sec}}{\text{rpm}}\right)$		50.86 rad/in		3.5 in/sec

Loaded Motor speed	/	Gear Ratio	=	No Load Velocity Limit
1411 rpm $\left(\frac{2\pi}{60}\ \frac{\text{rad/sec}}{\text{rpm}}\right)$		50.86 rad/in		2.9 in/sec

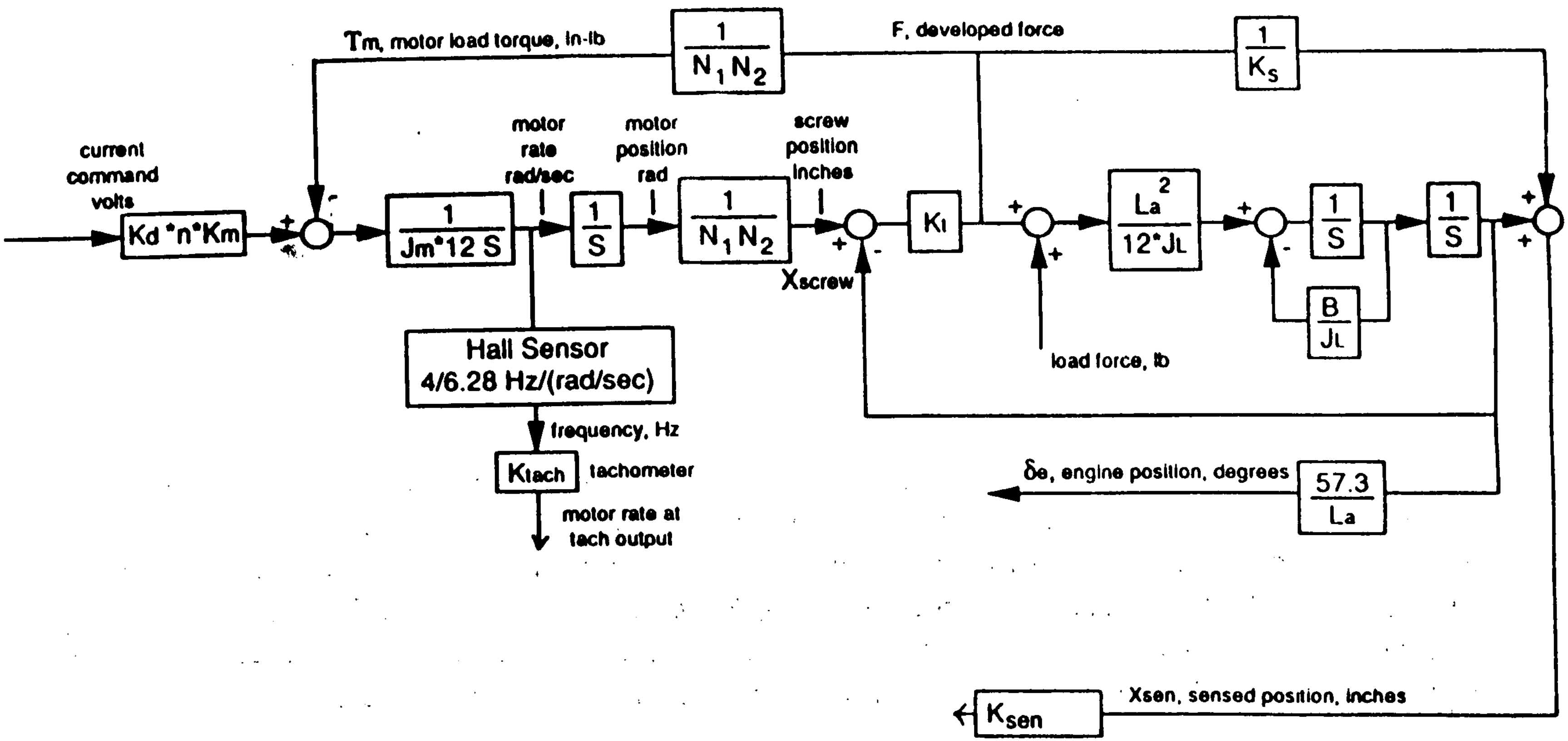


LOAD CAPABILITY AND VELOCITY LIMITS REQUREMENTS ACHIEVED

The "strawman" motor/actuator design is validated by verifying that the output load capability, no load motor speed, and loaded motor speed performance requirements are satisfied. The output load capability (29960) is computed by multiplying the stall current (81 amps) by the torque sensitivity (.303 ft-lb/amp), gear ratio (50.86 rad/in), and number of motors (2). The velocity limits are calculated by dividing the no load/loaded motor speed by the gear ratio. The loaded motor speed of 1411 rpm was obtained using the torque-speed curve shown above and selecting the spec'd load torque corresponding to a 20000 lb force.

MOTOR/ACTUATOR/LOAD DYNAMICS MODELED & SIMULATED

Honeywell



MOTOR/ACTUATOR/LOAD DYNAMICS MODELED & SIMULATED

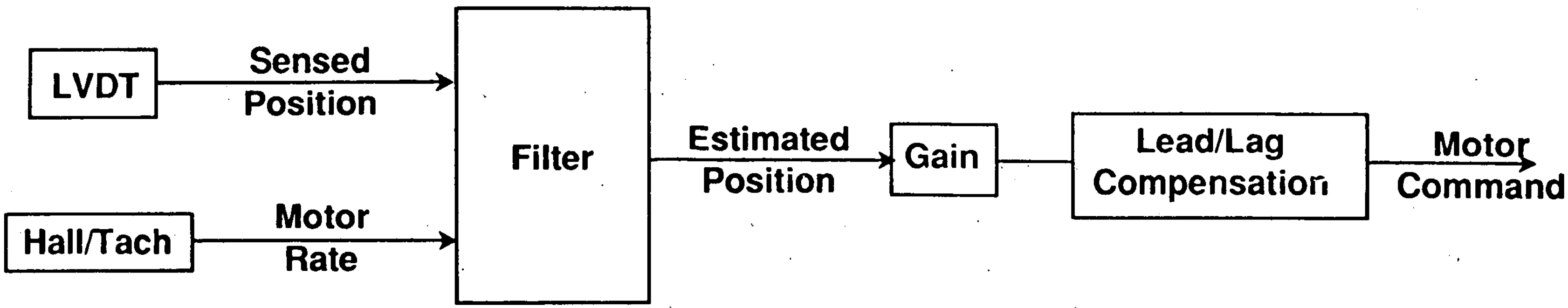
The block diagram above mathematically represents the dynamic behavior of the motor, actuator, and load. The open loop transfer function between the motor input command voltage and the position outputs defines a fourth order system (4 integrators, where S is the Laplace transform variable). The characteristic roots are therefor defined by a quartic equation containing a single complex root pair describing the load dynamics and a single first order root and free integrator root defining the motor/actuator.

The motor drive circuitry bandwidth is very high with respect to the motor/actuator/load dynamics and can be modeled as a simple gain Kd. The motor torque is computed by multiplying the motor current by the number of motors (n) and the torque sensitivity (Km) and then subtracting the load torque feedback (Tm). The motor rate is computed by dividing the commanded torque by the motor inertia (Jm) and integrating. Integrating the motor rate yields the motor position. The screw position is computed by dividing the motor position by the coupling ratio (1/N1N2). The developed force across the actuator is computed by multiplying the actuator stiffness (Kt) by the difference between the screw and engine positions. The engine load acceleration is computed by dividing the developed force by the load mass ($La^2/(12 * JL)$). The load dynamics are modeled as a second order very lightly damped system. Load damping is defined by the magnitude of the parameter B.

Two sensors are used for feedback control. An LVDT senses screw position and a Hall Sensor/Tach senses motor rate.

Minimal Order Feedback Control Structure Minimizes Implementation Complexity And Cost

Honeywell



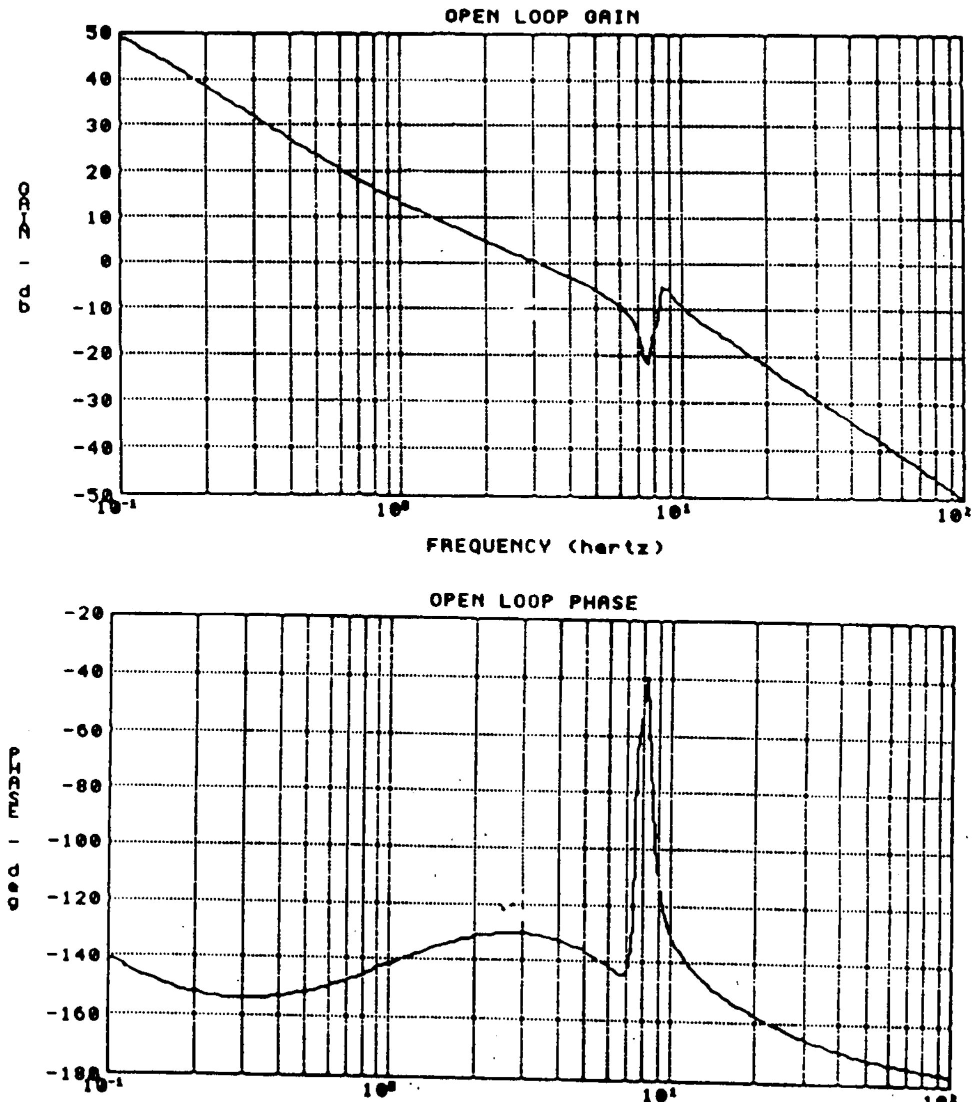
Filter phase stabilizes motor/load dynamics (quadratic dipole)
Patent Awarded

MINIMAL ORDER FEEDBACK CONTROL STRUCTURE MINIMIZES IMPLEMENTATION COMPLEXITY AND COST

A unique control structure has been defined that results in a minimal order system and as a result reduces implementation complexity and cost. The structure includes a filter which combines sensed position from an LVDT and motor rate from a Hall/Tach sensor. This not only results in an excellent broadband estimate of engine position but also phase stabilizes the motor/load dynamics (lag/lead quadratic dipole). Desired stability margins are achieved by simple lead/lag loop shaping and gain selection.

STABILITY MARGINS ARE ACCEPTABLE

Honeywell



Gain Margin = ∞

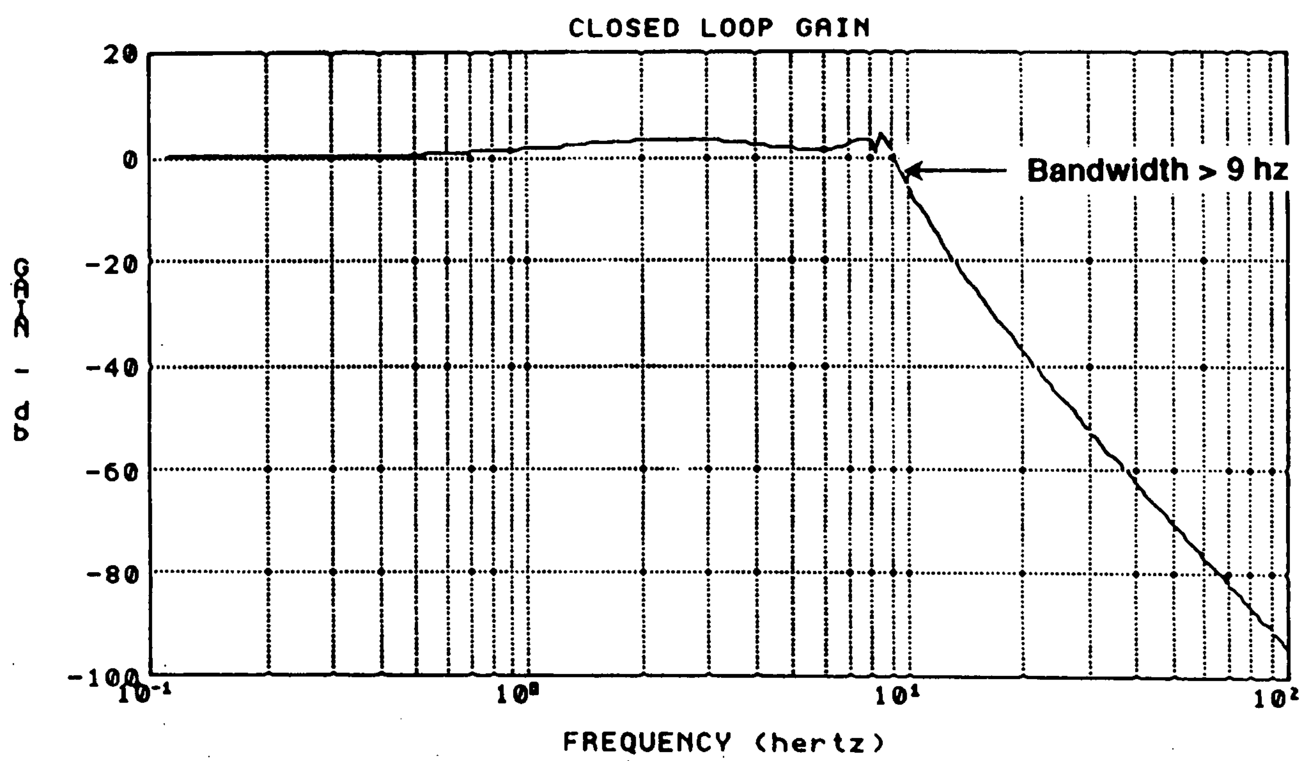
Phase Margin = 50°

STABILITY MARGINS ARE ACCEPTABLE

The open loop frequency response with the control loop broken at the position sensor is shown above. The gain and phase margins are computed from these two plots. At the 0 db crossover frequency of 3 hz, the system phase is -130 deg. Therefore, the phase margin is $-130° + 180° = 50°$. The system phase never reaches -180°, therefore the gain margin is infinite.

COMPARABLE DYNAMIC RESPONSE IS PREDICTED

Honeywell

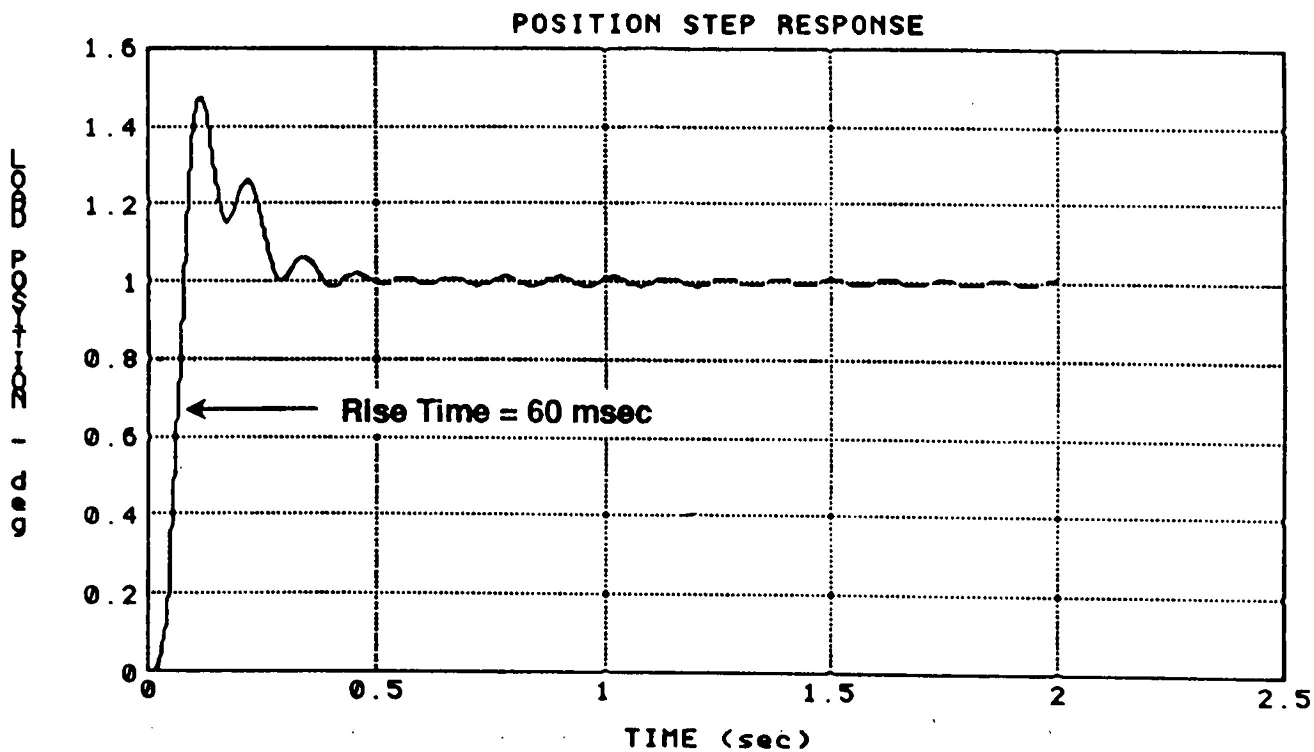


COMPARABLE DYNAMIC RESPONSE IS PREDICTED

The closed loop frequency response (sensed position/commanded position) is shown above. A 9 Hz bandwidth (frequency @ -3db) exceeds the 8 hz bandwidth specification for Titan IV stage 1. The response is relatively flat out to 9 hz and then rolls off at 80 db/decade.

Step Response Is Fast And Well Behaved

Honeywell



STEP RESPONSE IS FAST AND WELL BEHAVED

The load position time response to a unit position step command is shown above. The rise time (60 msec) is very fast - indicative of the high bandwidth. The response shape is dominated by a well damped second order mode. The "ringing" present is due to a very lightly damped second order mode that represents the engine load dynamics. These oscillations become negligible after 2 seconds. The load position overshoot is approximately 40%.

Stage 1 TVC Actuation Performance Requirements Candidate Engine Startup Transient Solutions Evaluated

Honeywell

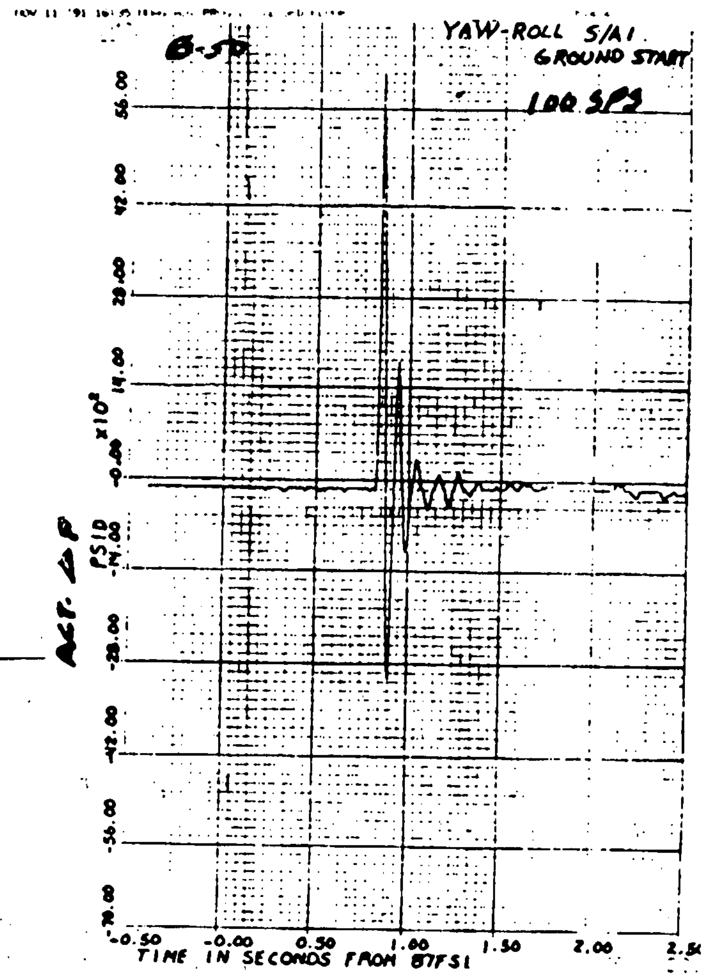
Approach	Philosophy	Implementation	Evaluation/Comments
Active Control	"Back drive" Actuator during startup transient	Sense load force, pass sensor output through a high pass filter and feedback as additional component of motor command	• Adds system damping • Force sensor dynamic range limit • Motor accelerations required exceed current state of the art capabilities • Motor inertia must be reduced by a factor of 5 to 10 for this approach to be feasible
Passive Control	Dissipate startup transient energy using passive mechanical elements	Spring/Damper in series with actuator	• Smaller actuator required when space is allocated for passive mechanical elements • Position offset for static loads • Weight penalty
Soften Actuator	Reducing stiffness reduces force developed at actuator	Appropriate material selection, screw cross section	• Constrains achievable bandwidth However, Stage 1 bandwidth rqmt's • Lowest cost, weight, technical risk solution

STAGE 1 TVC ACTUATION PERFORMANCE REQUIREMENTS
CANDIDATE ENGINE STARTUP TRANSIENT SOLUTIONS EVALUATED

A single active control and two passive control design approaches for attenuating the transient loads at engine startup have been evaluated. The philosophy behind each approach along with implementation requirements are presented above. At the present time, we believe that adjusting the actuator stiffness (to soften) is the best approach. We have been able to demonstrate for Titan IV stage 1 booster TVC, both closed loop frequency response performance, start up transient considerations, and position offsets under static loads can be met with current state of the art EMA's.

Stage 1 Engine Start Transient Modeled And Simulated Based On Test Data

Honeywell



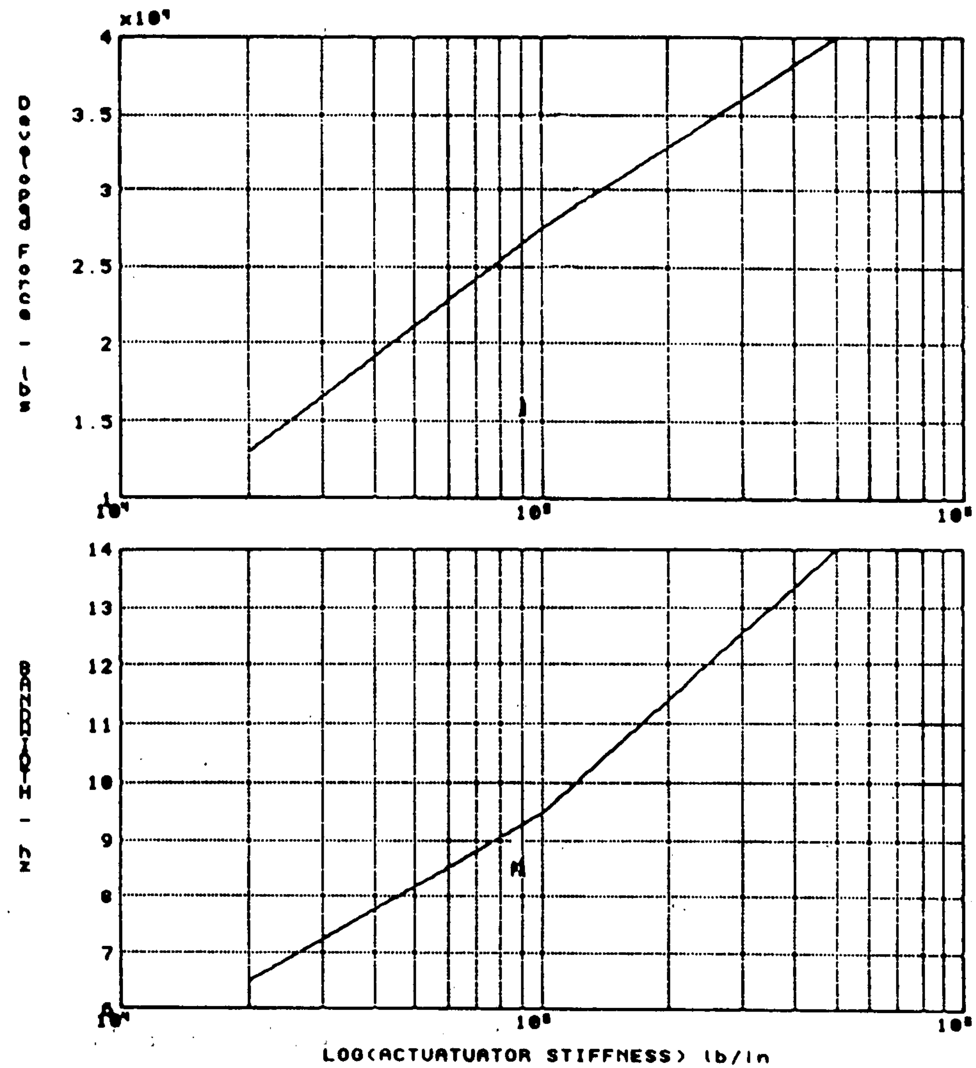
STAGE 1 ENGINE START TRANSIENT MODELED AND SIMULATED BASED ON TEST DATA

A worse case Titan IV stage 1 engine startup transient time history signature is shown above. Differential pressure (Δp) is plotted versus time (sec). The maximum Δp is seen to be approximately 6375 psid. For a piston area of 9.88 sq in, we can predict a worse case force of 63000 lb on the EMA. The engine start transient can be seen to have a duration of approximately 20 msec and be triangular in shape. The subsequent ringing after the startup transient (time > 20 msec) represents the hydraulic actuator response.

C-4

ACTUATOR STIFFNESS EFFECTS FORCE APPLIED TO STRUCTURE AND CLOSED LOOP BANDWIDTH (63,000 LB STARTUP TRANSIENT)

Honeywell



ACTUATOR STIFFNESS EFFECTS FORCE APPLIED TO STRUCTURE AND CLOSED LOOP BANDWIDTH (63,000 LB STARTUP TRANSIENT)

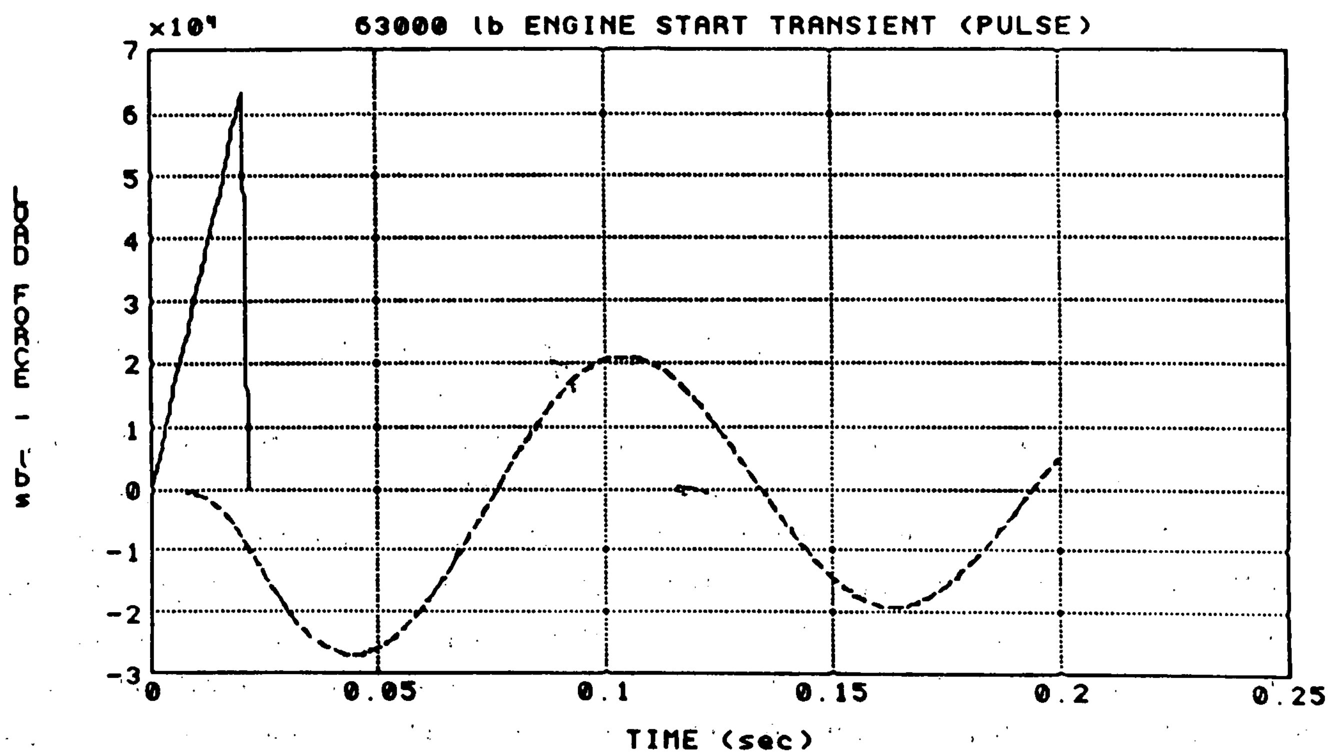
EMA developed force to a 63000 lb startup transient and achievable closed loop bandwidth are logarithmic functions of actuator stiffness as shown above. Cutting the transient induced force developed across the EMA in half requires reducing the actuator stiffness by a factor of 10. But reducing the actuator stiffness by a factor of 10 cuts the achievable bandwidth by a factor of two. Therefore, a compromise between bandwidth and transient induced EMA forces must be made. The range of suitable actuator stiffnesses (Ka) is bounded by the 30000 lb maximum developed force envelope and the 8 hz closed loop bandwidth requirement s. The actuator stiffness corresponding to these two requirements can be directly read off the above plots, i.e.

$$45000 \text{ lb/in} < Ka < 130000 \text{ lb/in}.$$

An actuator stiffness of 100000 lb/in was selected for subsequent analysis.

ACTUATOR STALL FORCE NOT EXCEEDED DURING WORST CASE STARTUP TRANSIENT (ACTUATOR STIFFNESS = 100,000 LB/IN)

Honeywell

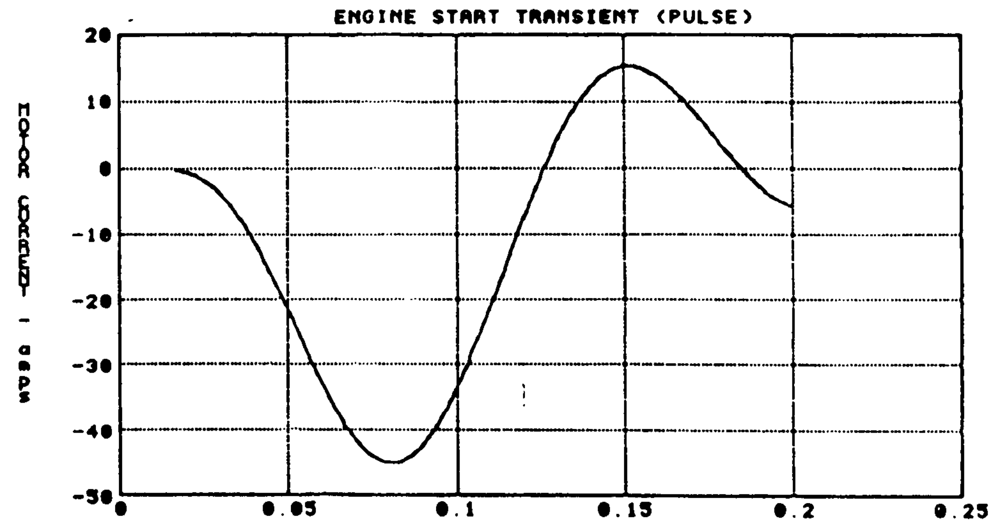


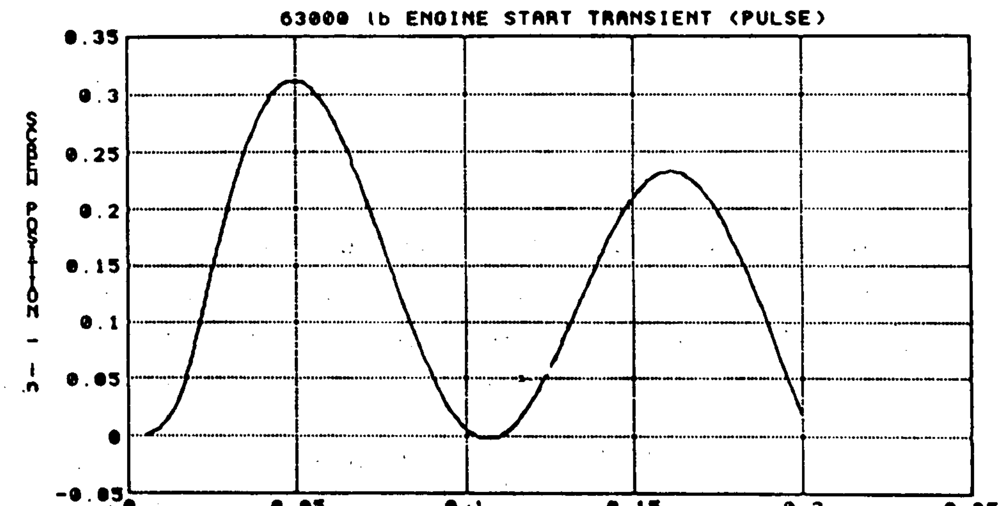
ACTUATOR STALL FORCE NOT EXCEEDED DURING WORST CASE STARTUP TRANSIENT (ACTUATOR STIFFNESS = 100,000 LB/IN)

The solid line in the above time history trace represents the engine start transient applied as a load force disturbance. The dashed line represents the resulting developed force across the EMA. The peak developed force (28000lb) occurs just prior to 50 msec. Given an actuator with a 100000 lb/in stiffness, our analysis predicts that the developed force to a worse case startup transient will not exceed the 30000 lb specification.

Saturation Current And Stroke Limits Avoided During Worst Case Startup Transient (Actuator Stiffness = 100,000 lb/in)

Honeywell





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SATURATION CURRENT AND STROKE LIMITS AVOIDED DURING WORST CASE STARTUP TRANSIENT (ACTUATOR STIFFNESS = 100,000 LB/IN)

The above two plots demonstrate that the engine startup transient load alleviation is accomplished without exceeding the current capabilities of the motor (81 amps) and the actuator stroke (± 1 in).

SESSION IV

ELA PROTOTYPE DESIGNS AND TEST RESULTS

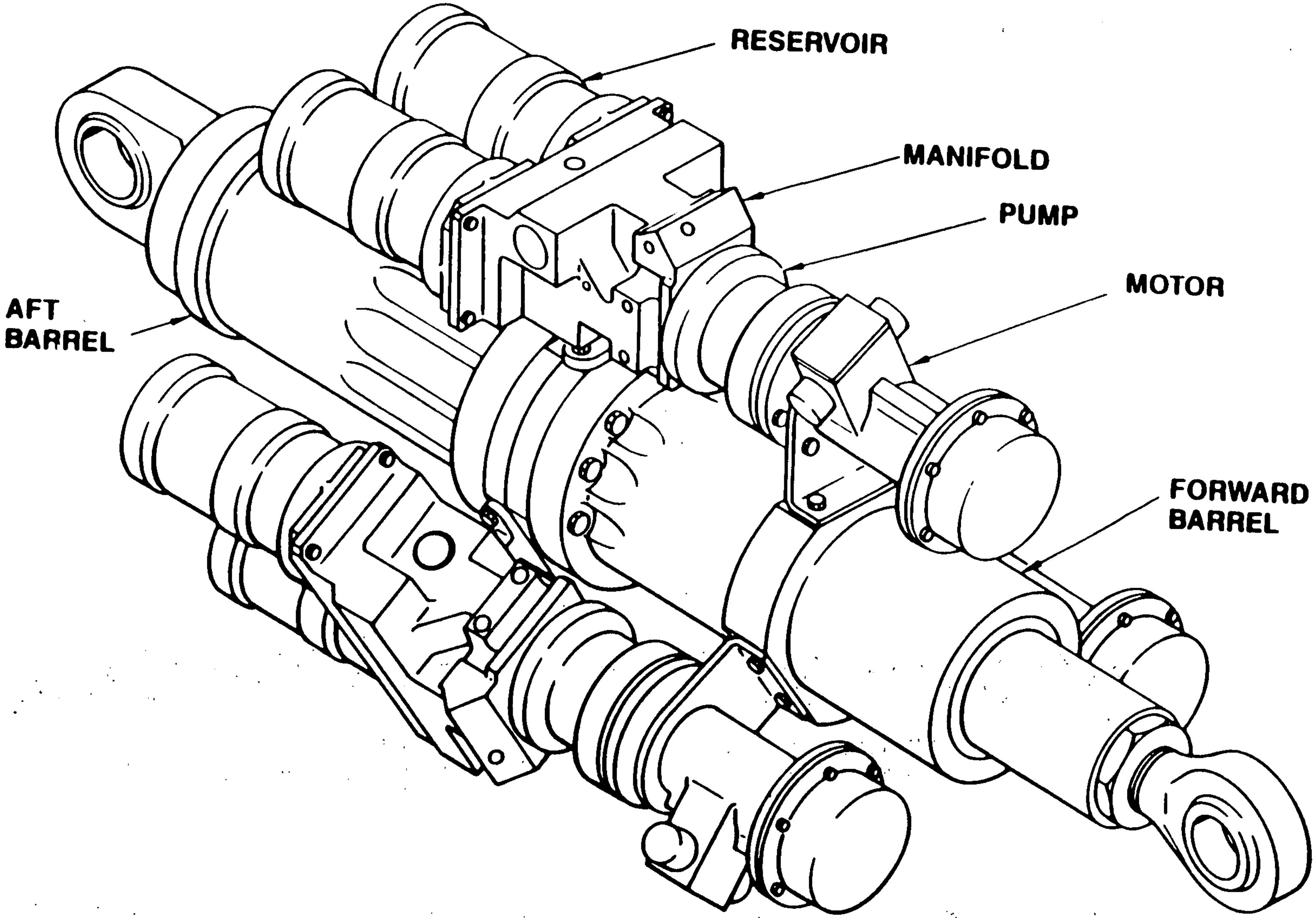
EHA Prototype Demonstration

NASA Electrical Actuation Technology Bridging Workshop @ MSFC

9/29/92

Mike Kirkland
Allied-Signal

EHA ASSEMBLY



1992 IR&D ELECTROHYDROSTATIC ACTUATOR (EHA)

BASIC COMPONENTS OF THE 3-CHANNEL SYSTEM

1992 IR&D EHA DESIGN

- FAIL OPERATE - FAIL-SAFE
  - NO SINGLE POINT FAILURE MODES OTHER THAN STRUCTURE/MOUNTING
  - A SINGLE FAILURE LEAVES TWO CHANNELS FULLY OPERATIONAL. AFTER A SECOND FAILURE, ONE CHANNEL IS STILL OPERATIONAL AT DIMINISHED HP.
- MODULARIZED DESIGN
  - THREE 8.3-HP POWER MODULES MOUNTED ON A TRIPLEX ACTUATOR (25-HP TOTAL)

  NOMINAL LENGTH: 47.33 INCHES

  STROKE: ± 5.7 INCHES

3-channels provide fail-op - fail-safe capability.

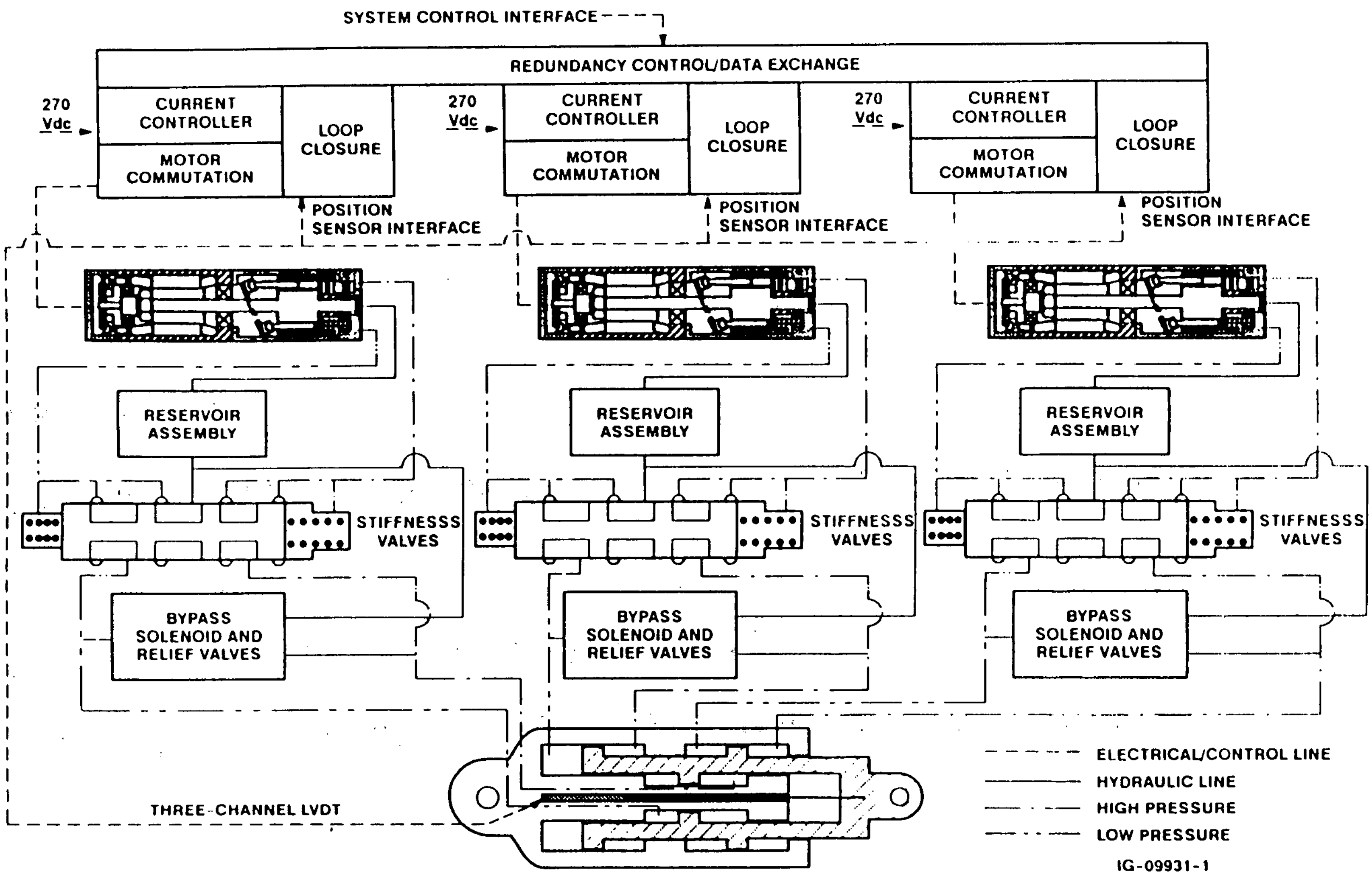
EHA PERFORMANCE

PRESENT CONFIGURATION:	HALF-SIZE MOTOR/PUMPS FULL-SIZE ACTUATOR/MANIFOLDING
OUTPUT HP:	25 (3 CHANNELS FORCE SUMMED)
RATE:	3.3 IN./SEC
FORCE:	50,000 LB. GENERATED (ABLE TO WITHSTAND 100,000 LB.)

The EHA is presently configured with motors one-half the horsepower of the eventual NLS configuration.

Upgrade can be accomplished by replacing the motor/pump assemblies.

IR&D EHA SYSTEM SCHEMATIC



EHA schematic illustrates redundancy and isolation of the three channels for fault-tolerant operation.

Operation of the bypass valve of any one channel connects both pressure sides of the piston to reservoir effectively disconnecting the failed channel.

EHA ADVANTAGES

HIGH RELIABILITY
- No Single-Point Failure Mode

MATURE TRANSIENT LOAD PROTECTION
- Hydraulic Relief Valve

MATURE FAILED CHANNEL DECOUPLER
- Hydraulic Bypass Valve (solenoid operated)

WET MOTOR
- Hydraulic Fluid Cools Motor
- Cooler Running Motor is More Reliable
- Allows Smaller Motors with Lower Inertia
- Lower Weight Motors and Controllers

HYDRAULIC CHARACTERISTICS
- Inherent Damping
- Zero Backlash

The EHA provides the well understood advantages of hydraulics along with the energy-saving advantage of power on demand electric actuation.

TRANSIENT TEMPERATURES FOR EHA MOTOR / PUMP

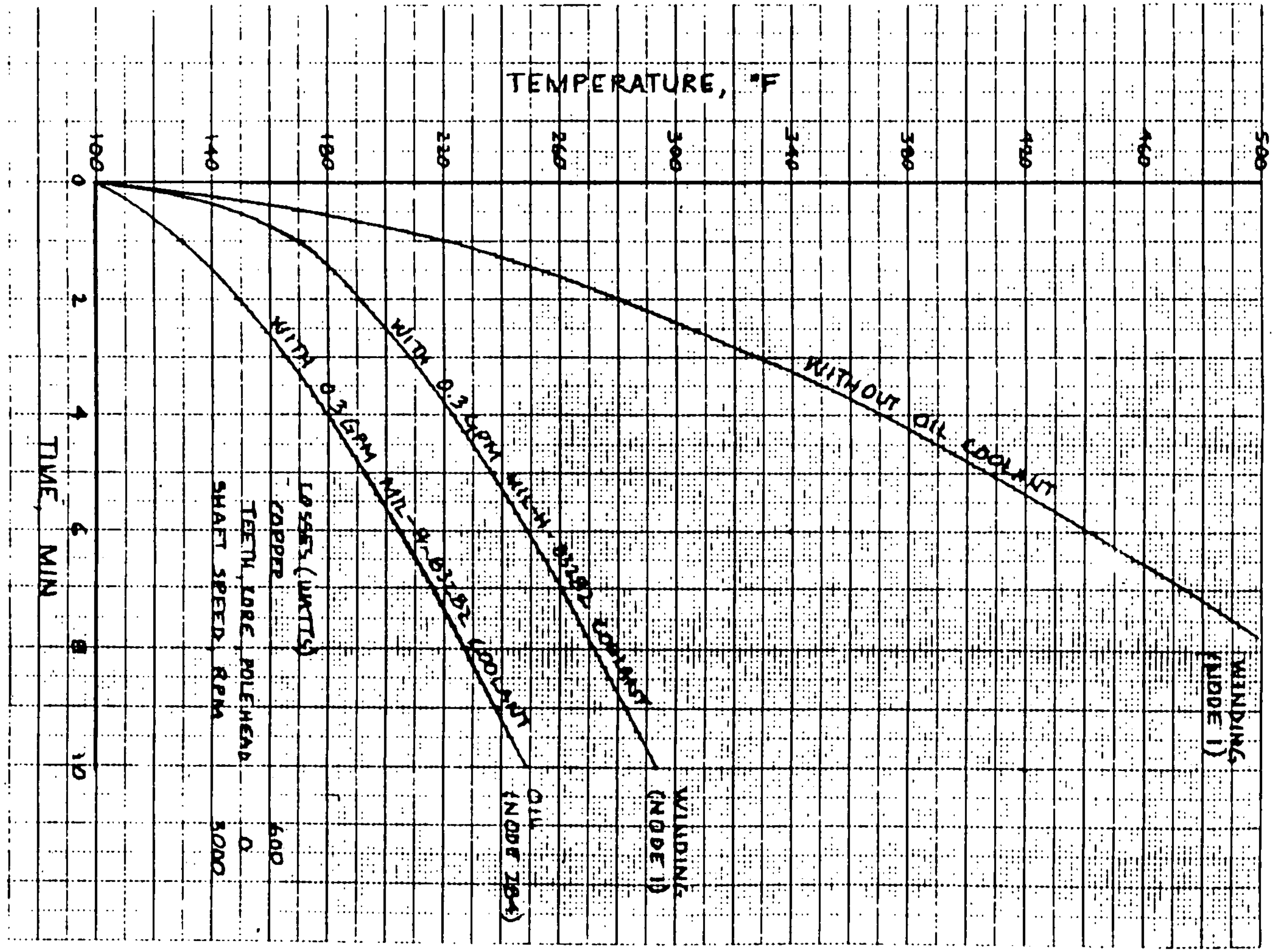


Chart shows the advantage of the EHA wet motor. Without coolant, the motor winding temperature would be considerably higher. Analysis was performed for continuous 70% (extremely conservative) of peak horsepower for a 10-minute mission. Winding temperature remains below 300°F.

IR&D EHA
BUILT-IN TEST CAPABILITY

EXISTING CAPABILITIES	ADDITIONAL FAULT TOLERANT CONTROLLER TECHNOLOGY
ROMTEST RAMTEST	Comparison of Multiple Position Feedback Signals
A/D Test CPU Test	Comparison of Multiple Motor Speed Signals
Power Supply Test Watch Dog Timer Test Inverter Test	Eliminate Faulty Feedback Signals Using Only Healthy Signals for All Control Channels

Inverter Overtemperature
Motor Overcurrent
Motor Overspeed
Reservoir Level Sensor
Position Sensor Fail
Bypass Valve Continuity
Excitation Fail
    Motor Rotor Position
    LVDT
    Current Sensor
	Soft Failure Detection - Degraded Performance of One Channel Compared to Others

The EHA digital controller provides extensive health monitoring capabilities. Recent advancements incorporating interchannel communication and exchange of data provides more reliable load sharing, fault masking capability and soft failure detection.

EHA DEMONSTRATION at NASA 9/29/92

Test Configuration: Speed Limit - 2.9 in/sec; Current Limit - 15 amps/motor

1) OPERATION WITH TWO CHANNELS (SINGLE FAULT SIMULATION)
   - A. Sine Command, 0.1 Hz, ± 3 in amplitude
   - B. Sine Command, 0.5 Hz, ± 1 in amplitude
   - C. Frequency Sweep 1 to 10 Hz, ± 0.1 in amplitude
   - D. Step Command ± 0.5 in, ± 1.0 in, ± 2.0 in at 0.15 Hz

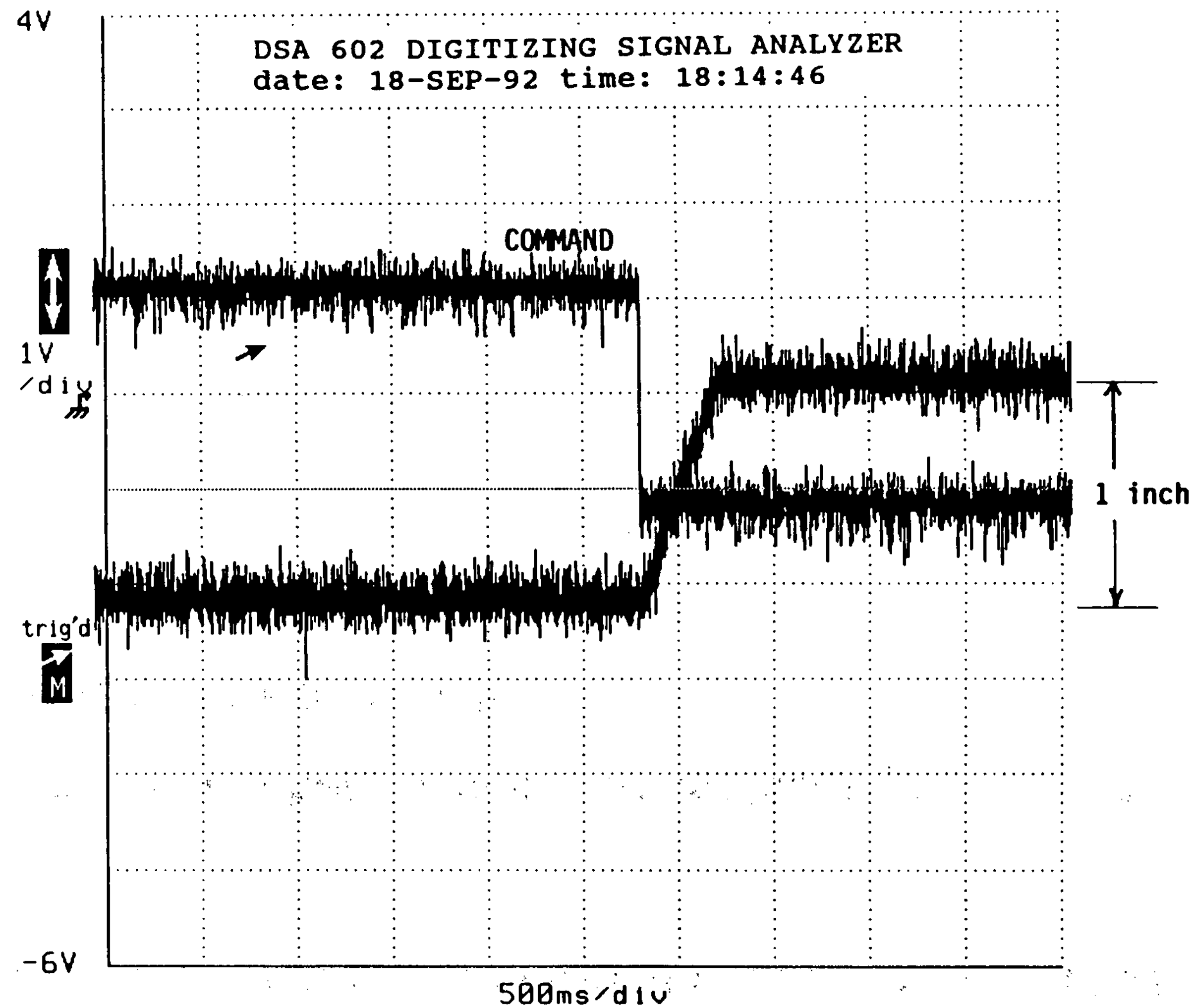
2) SINGLE CHANNEL OPERATION (SIMULATION OF SECOND FAULT)
   - A. Sine Command, 0.1 Hz, ± 3 in amplitude
   - B. Sine Command, 0.5 Hz, ± 1 in amplitude

IMPROVED PERFORMANCE IS EXPECTED IN FUTURE TESTING WITH INCREASED SPEED AND CURRENT LIMITS

Sequence of tests for demonstration of the EHA at NASA MSFC.

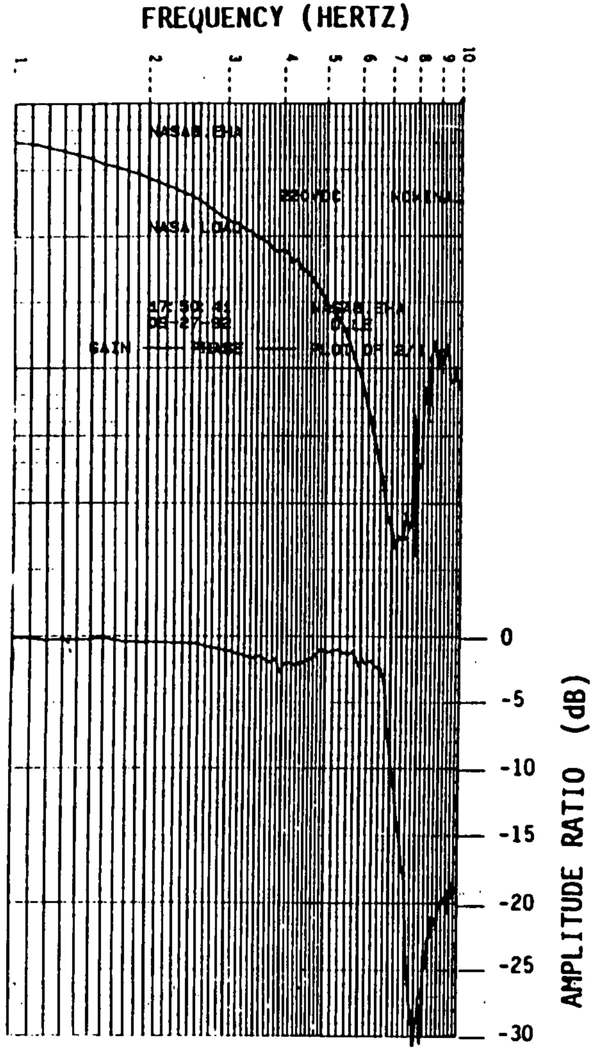
The actuator has just begun development testing and has not yet been adjusted to its full capacity.

EHA STEP RESPONSE
(20,000 lb. load; 1-inch step)
Speed Limited to 2.3 in/sec



Preliminary test results at Allied Signal with 20,000 lb. load mass and 2.3 in/sec speed limit. Step response data shows zero overshoot.

EHA FREQUENCY RESPONSE
(± 0.1 in.; NASA Test Load 9/27/92)



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EHA frequency response testing at NASA MSFC. Data illustrates actuator capability of 6.7 Hz at -3 dB.

EHA IR&D PLANS THRU 1992

- COMPLETE PERFORMANCE CAPABILITY TESTING
  - Peak Load/Stall Load Testing
  - Increased Speed and Current Limit Testing
  - Testing with Increased Gains
- COMPLETE FABRICATION OF FAULT-TOLERANT CONTROLLER
- FAULT INJECTION/FAULT-TOLERANT DEMONSTRATION

Testing has just begun on the EHA. Testing to the full limits of the actuator capability are planned for this year.

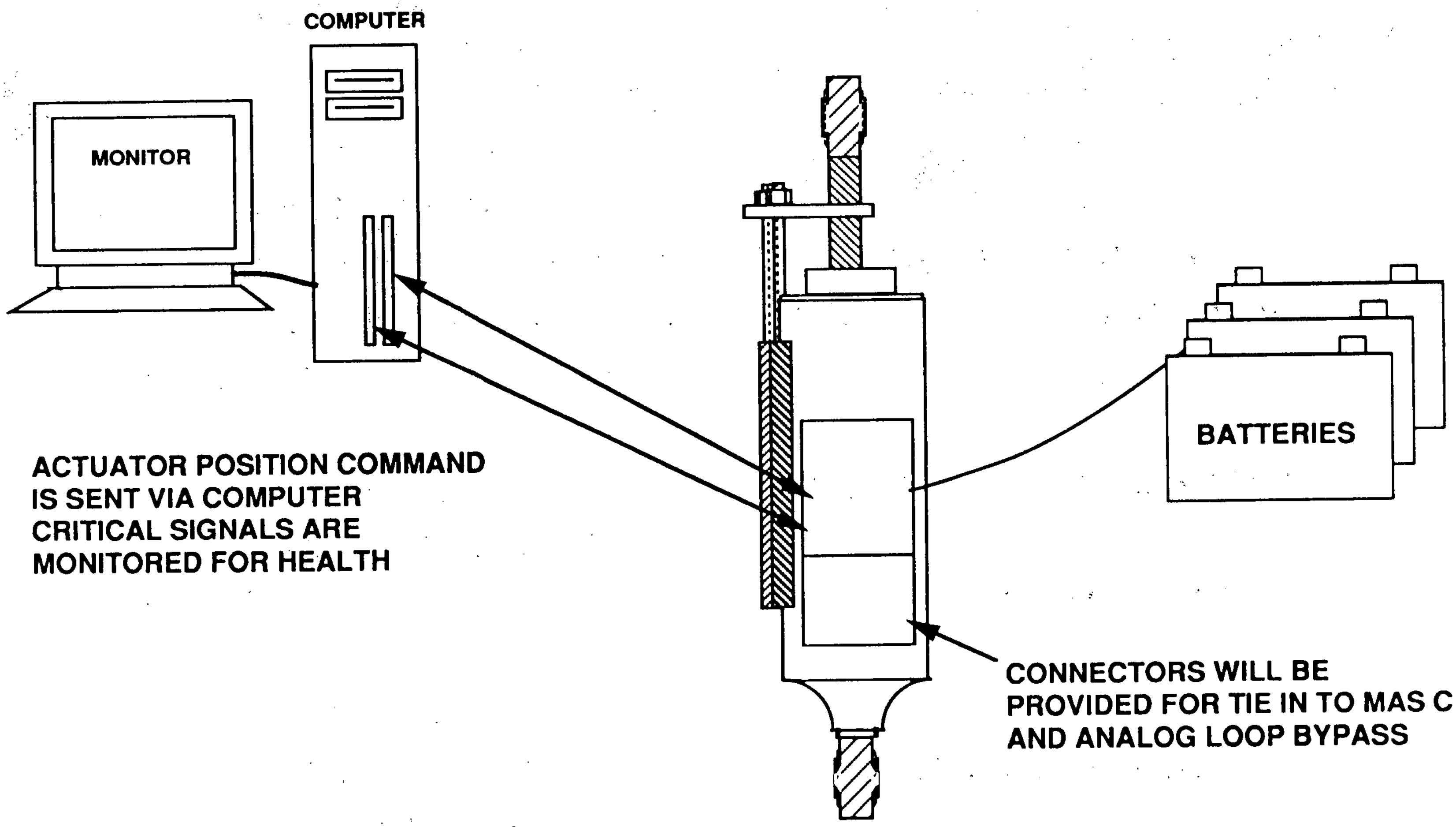
HONEYWELL EMA SYSTEM OVERVIEW

PRESENTED AT MARSHALL SPACE FLIGHT CENTER

SEPTEMBER 29, 1992

PRESENTED BY Z. ZUBKOW
HONEYWELL SPACE SYSTEMS GROUP
CLEARWATER, FLORIDA

EMA SYSTEM OVERVIEW



Honeywell

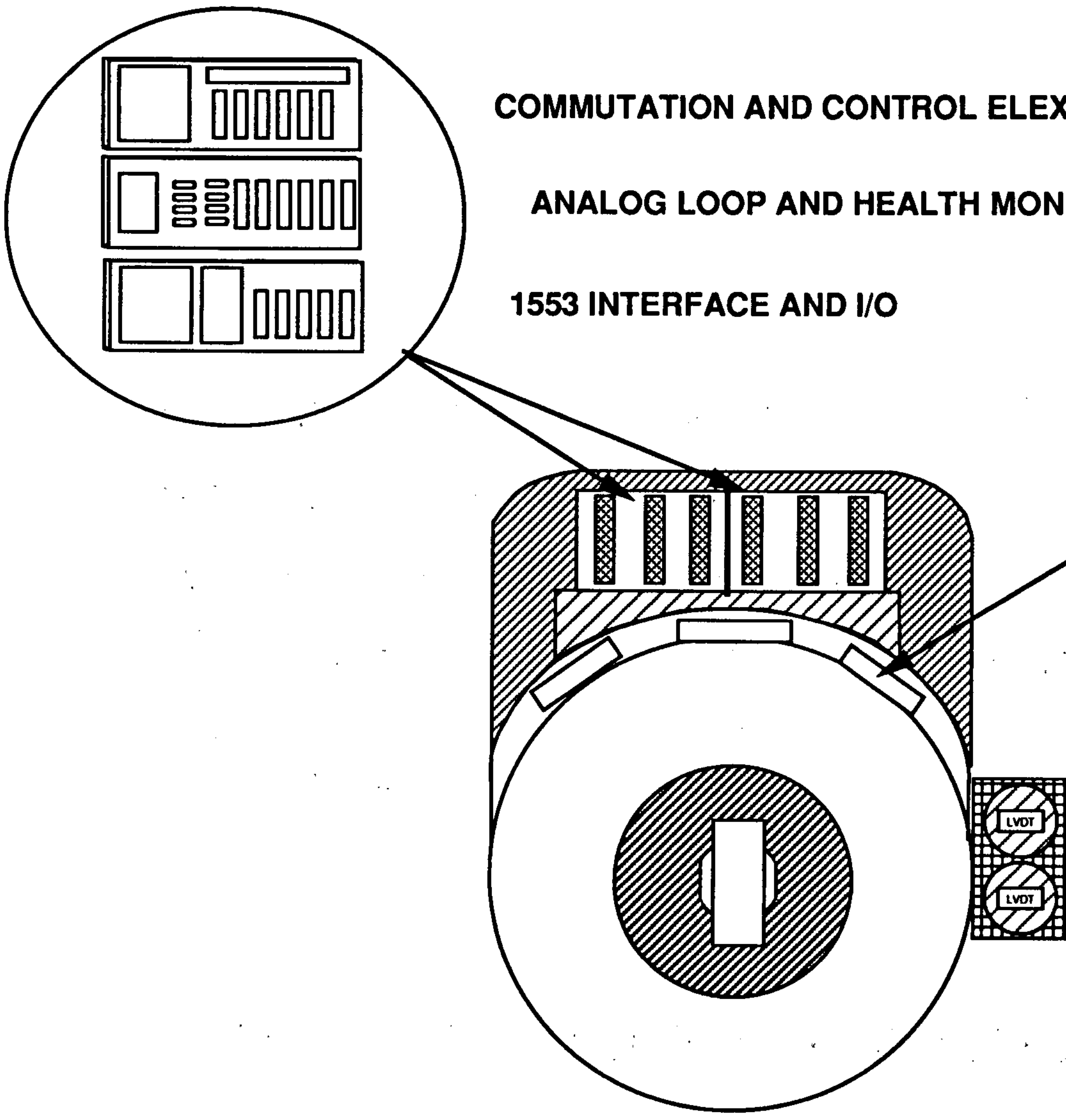
- USE HIGH TORQUE LOW SPEED MOTOR
  - ACTUATOR IS BACK-DRIVEABLE
  - VERY HIGH ACCELERATIONS ARE POSSIBLE DUE TO LOW GEAR RATIO

- USE REDUNDANT MOTOR WINDINGS ON COMMON SHAFT
  - NO CLUTCHES OR SPUR GEARS
  - FAILED MOTORS CAN BE ELECTRICALLY DISCONNECTED

- USE DC BRUSHLESS MOTOR
  - GOOD THERMAL DISSIPATION (NO COOLING REQUIRED)
  - SIMPLE ELECTRONICS (CAN BE MOUNTED RIGHT ON ACTUATOR)

INTEGRATED CONTROLLER WITH DUAL REDUNDANT MOTORS, DRIVERS AND ELEX

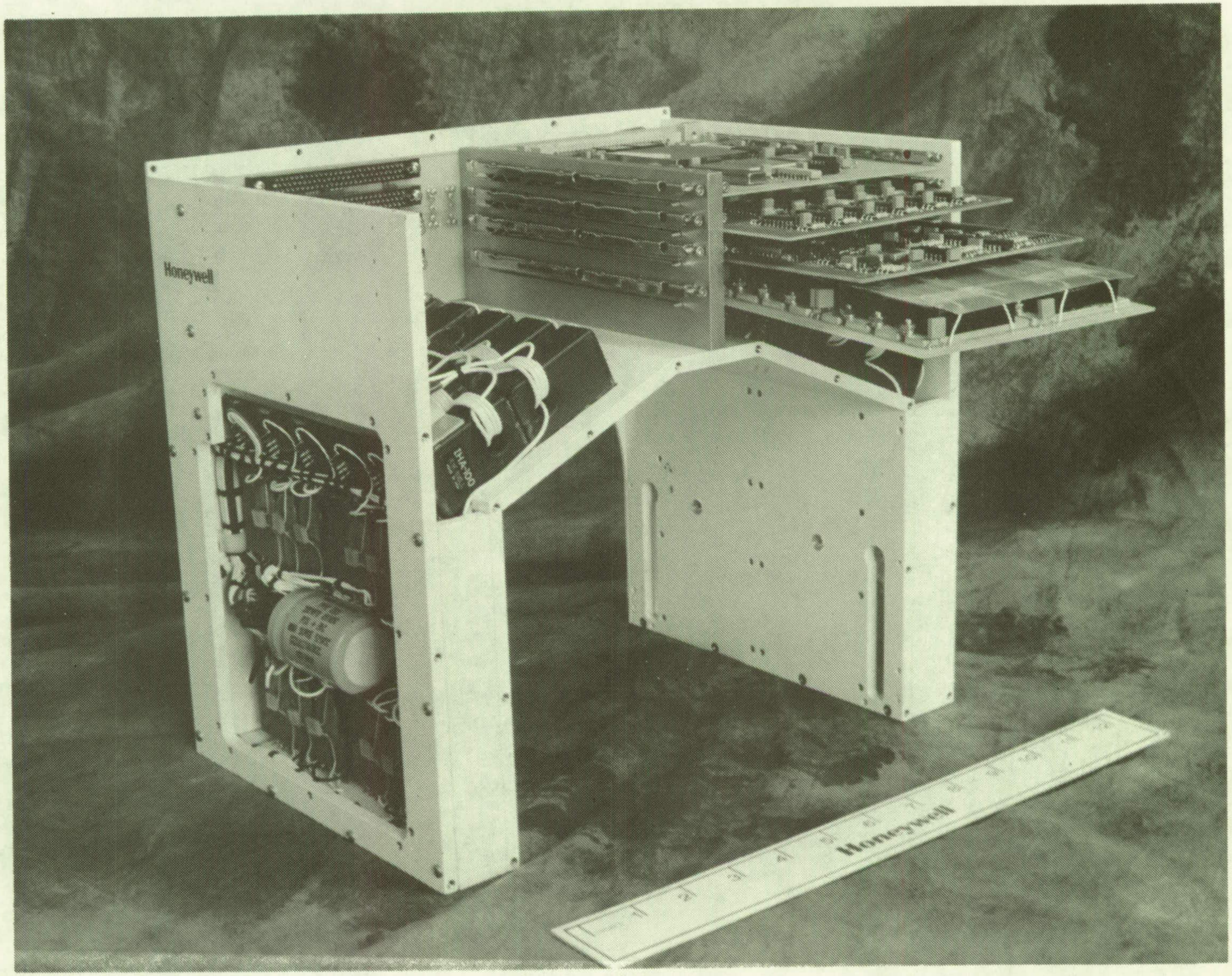
Honeywell



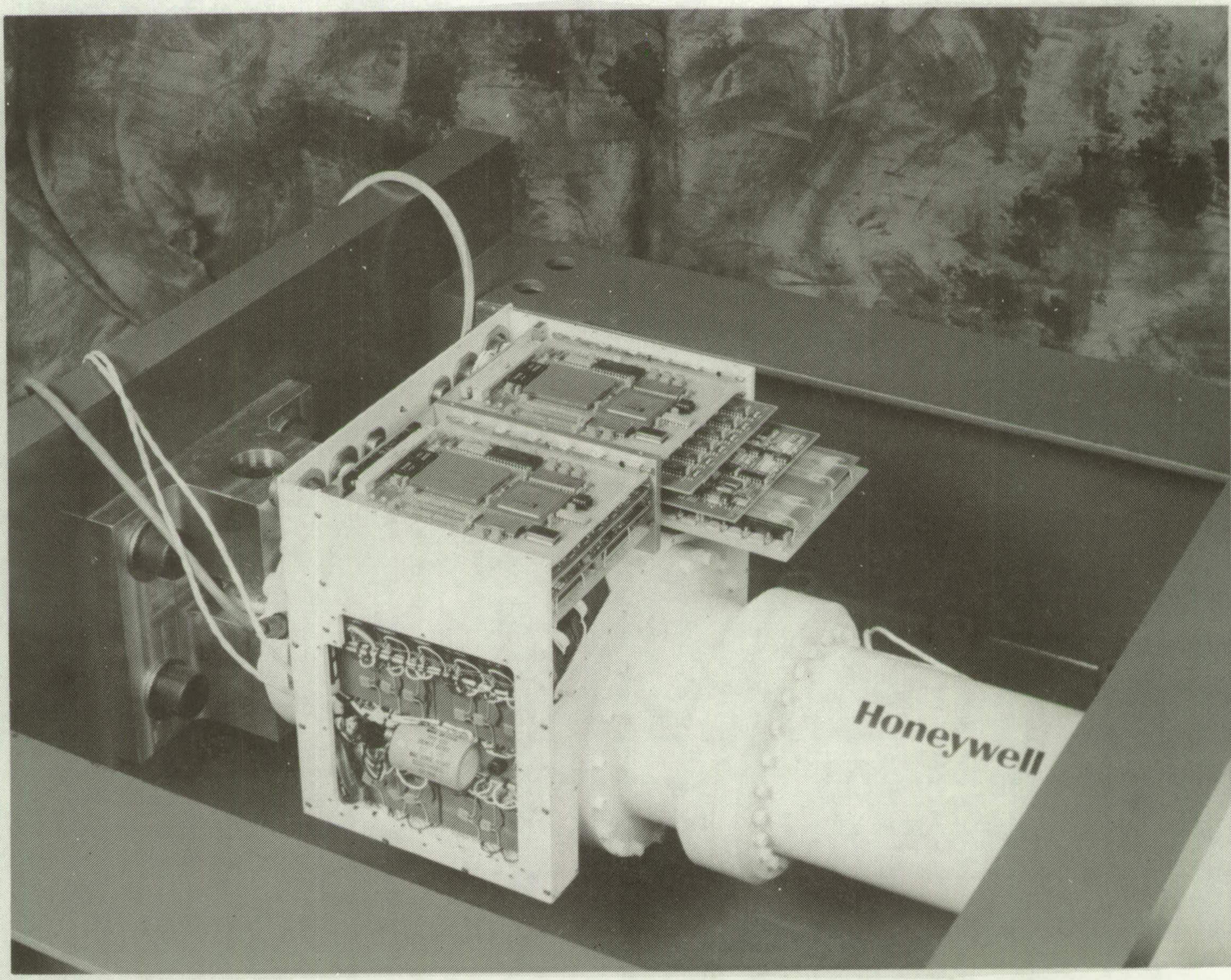
BENEFITS OF INTEGRATED CONTROLLER

- REDUCED EMI
  - HIGH POWER PWM LINES ARE VERY SHORT
- POWER LOSSES MINIMIZED SINCE PWM LINES ARE SHORT
- REDUCED LINE LENGTH OF LVDT SIGNALS
- NO EXTRA CONTROLLER BOX(S) REQUIRED
- SIMPLE CONSOLIDATED DESIGN

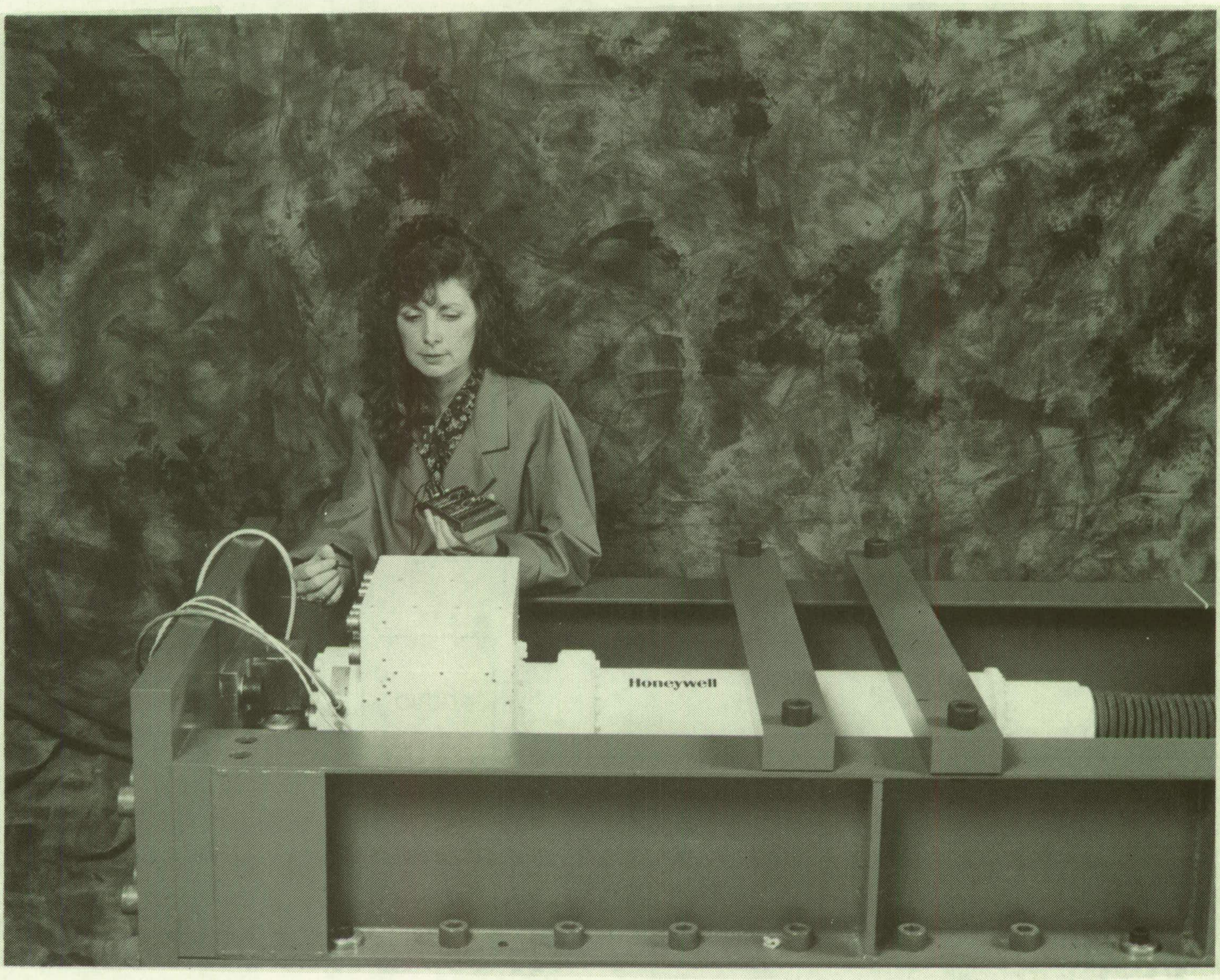
Dual Redundant 270 Volt 100 Amp Per Channel Controller



Integrated EMA and Controller

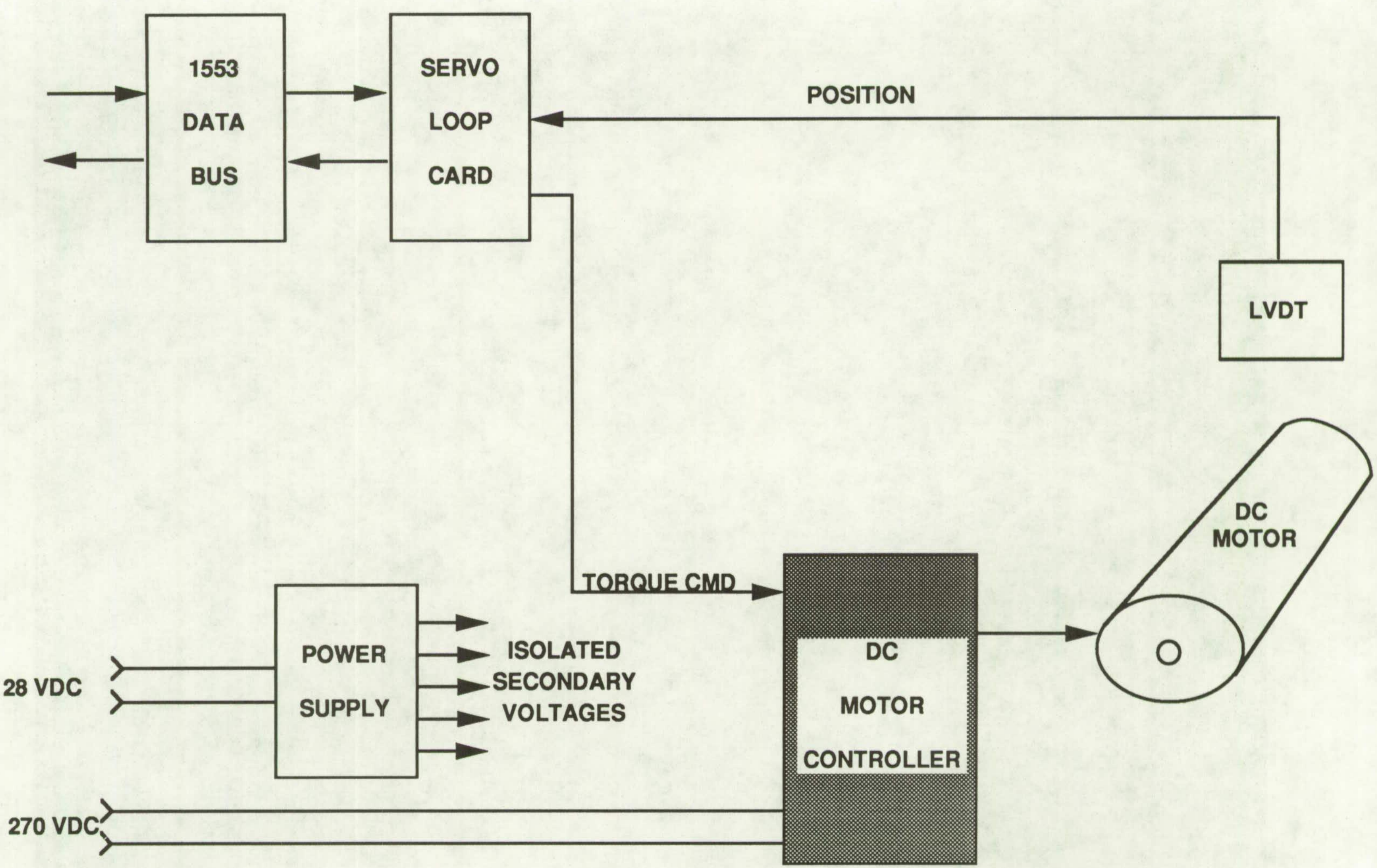


Integrated EMA and Controller In Testbed



EMA SYSTEM DIAGRAM

Honeywell

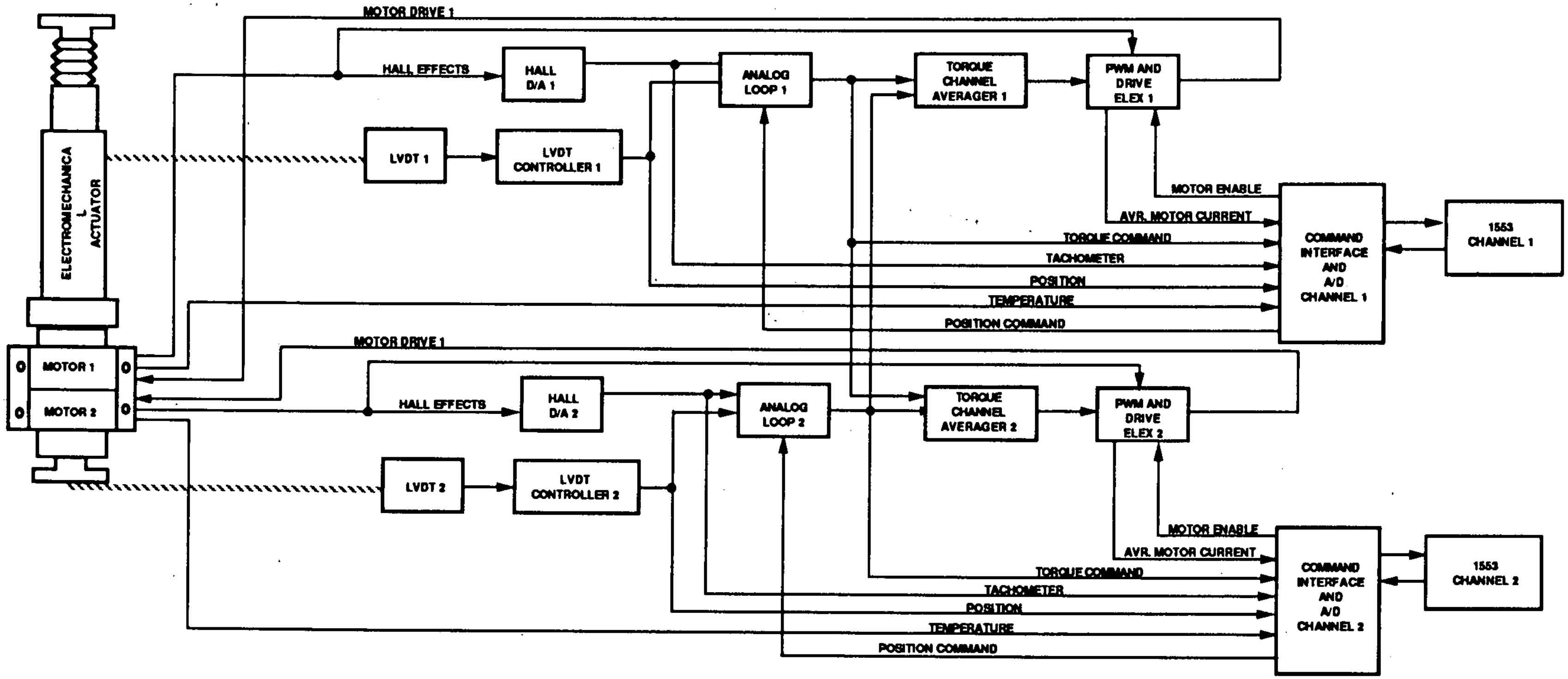


HONEYWELL SSG SYNERGY REDUNDANT ELECTRO-MECHANICAL ACTUATOR

30Mac56752

HONEYWELL / DURHAM

HONEYWELL / CLEARWATER



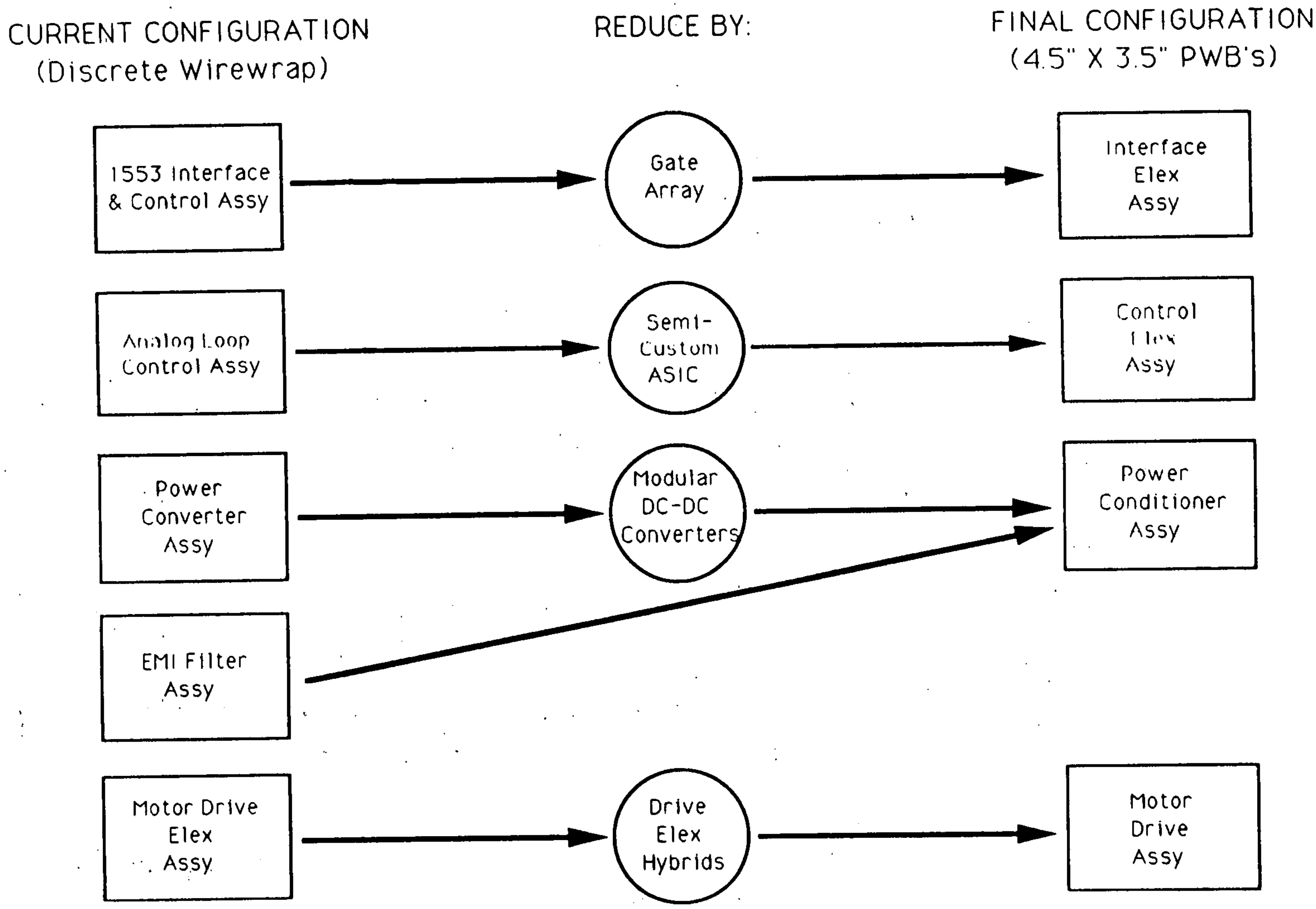
DC Brushless Motor
Actuator
PWM Drive
Electronics
LVDT
Tachometer

Redundancy
Architecture
Analog Control Loop
Torque Averager
Command Interface

LVDT Controller
Power Supplies
Computer Interface
Control / Display
Software

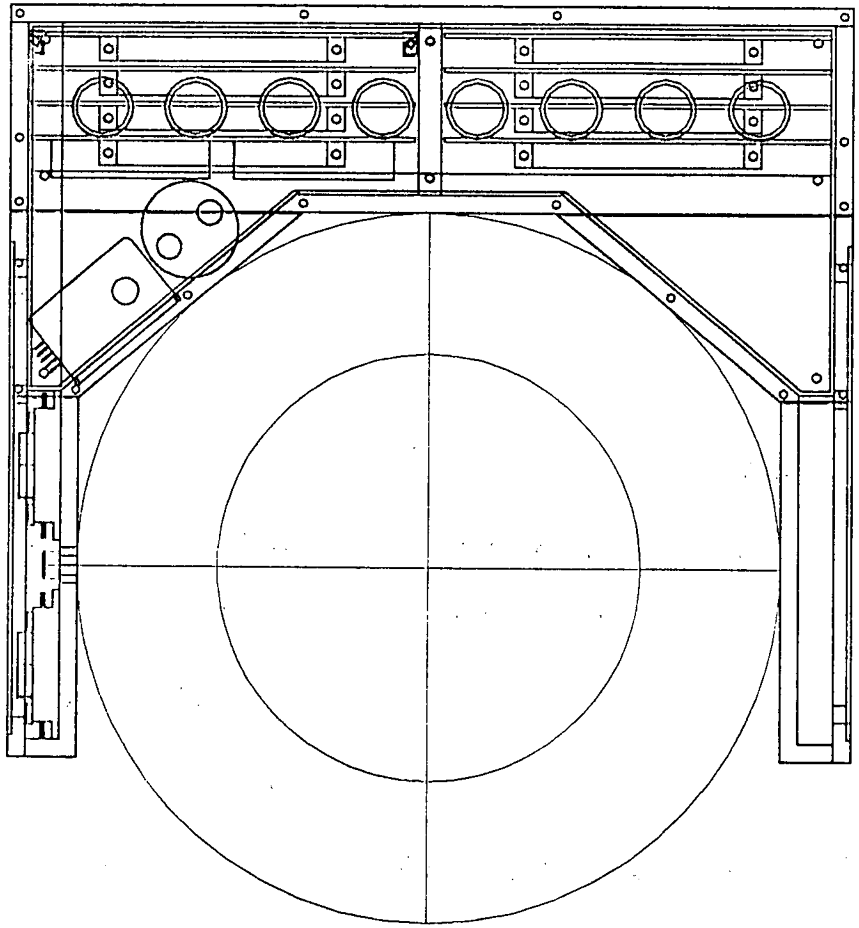
IZ1009

EMA CONTROLLER SIZE/WEIGHT/POWER REDUCTION



EMAZZ1020

28 HP EMA MECHANICAL OUTLINE



EMA HEALTH MONITORING

Honeywell

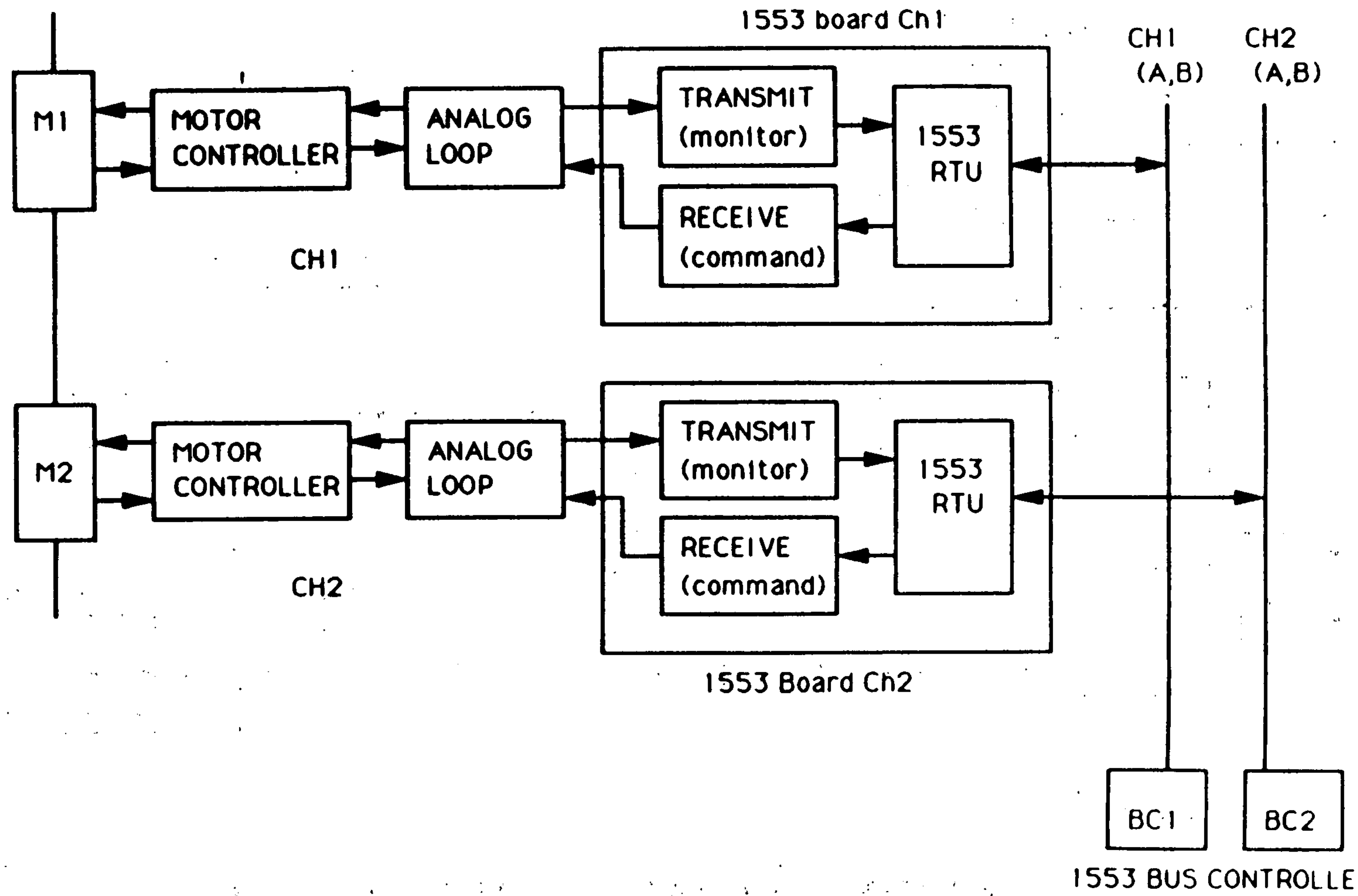
CRUCIAL SIGNALS ARE MONITORED AND SENT BACK VIA MIL-STD 1553 INTERFACE

- MOTOR CURRENTS
- LVDT POSITIONS (ACTUAL POSITION)
- COMMANDED POSITION (CHECKS D/A AND A/D FUNCTIONS)
- CURRENT COMMAND SIGNAL (FOR COMPARISON WITH ACTUAL MOTOR CURRENT)
- TEMPERATURE (THERMISTORS EMBEDDED IN WINDINGS OF EACH MOTOR)
- 1553 BUILT-IN-TEST
- LOW VOLTAGE POWER SUPPLY VOLTAGES
- TACHOMETER

SECOND STAGE
EMA

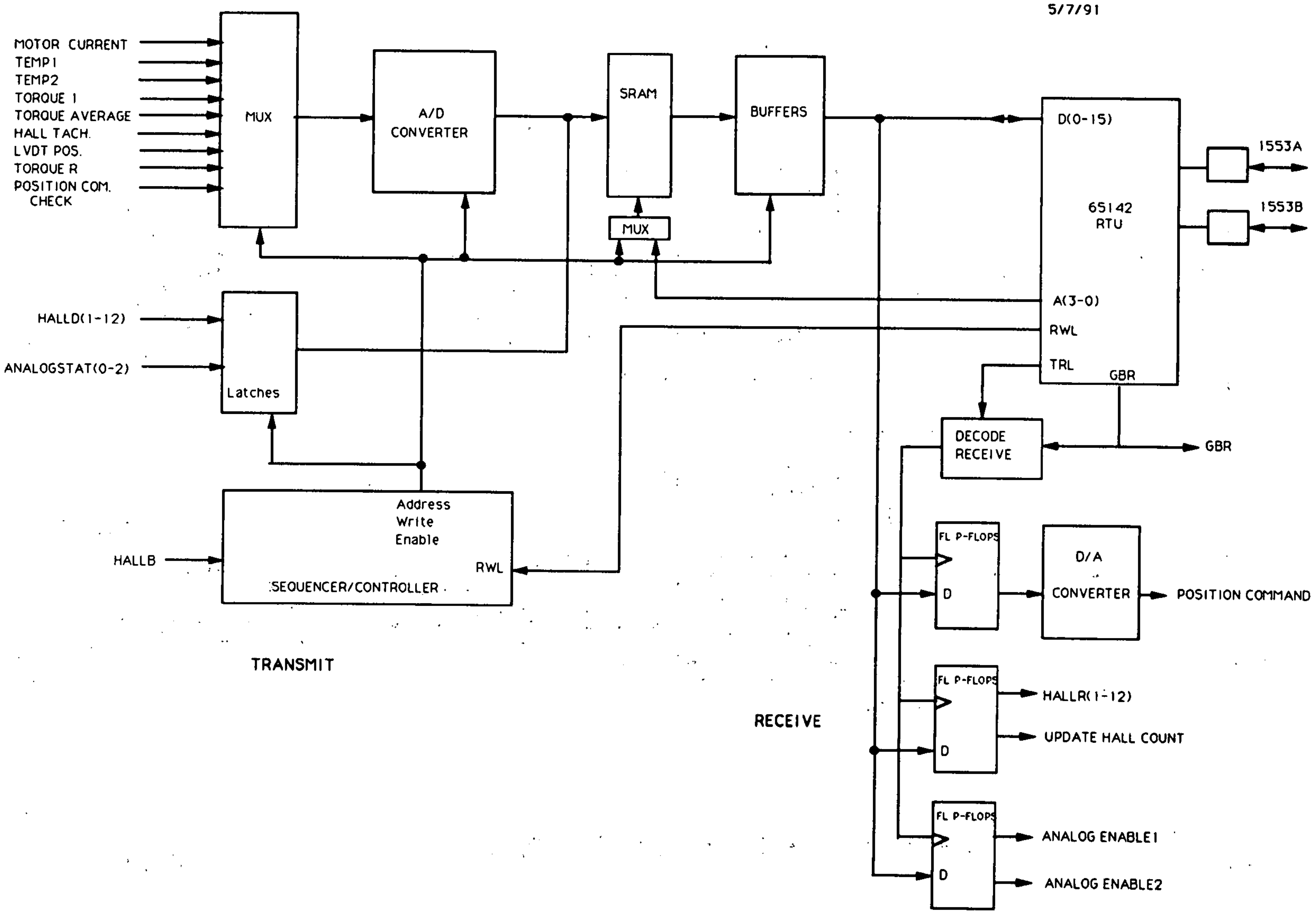
1553 TOP LEVEL DESIGN CONCEPT

Designer:
Richard Herrera
5/7/91



1553 RECEIVE/TRANSMIT FUNCTIONS

DESIGNER:
RICHARD HERRERA
5/7/91



EMARH1015

SECOND STAGE
EMA

RECEIVE DATA FORMAT

DESIGNER:
RICHARD HERRERA
5/7/91

RECEIVE FROM BUS CONTROLLER

- A COMMAND TO RECEIVE THREE DATA WORDS WILL BE ISSUED BY THE BUS CONTROLLER TO THE EMA RTU EVERY 50HZ.

RTU ADDRESS	T/R_	SUBADDRESS FIELD	WORD COUNT
00010	0	00001	00011

FIRST WORD RECEIVED

LSB

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
X	X	X	X												

POSITION COMMAND (D/A CONVERTER)

DIGITAL INPUT CODING	
DATAWORD	OUTPUT VOLTAGE
000H	+10V
3FFH	0.00 V
FFFH	-10V

SECOND WORD RECEIVED

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
X	X	X	UHC	R12											R1

HALLR1-HALLR12

UPDATE HALL COUNT BIT

0 = DONT UPDATE

1 = UPDATE

THIRD WORD RECEIVED

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
X	X	X	X	X	X	X	X	X	X	X	X	X	X	AE2	AE1

ANALOG ENABLE1 (BIT0)

0 = DISABLE
CHANNEL1
1 = ENABLE
CHANNEL 1

ANALOG ENABLE2 (BIT1)

0 = DISABLE
CHANNEL2
1 = ENABLE
CHANNEL 2

MARH1014

SECOND STAGE
EMA

TRANSMIT DATA FORMAT

DESIGNER:
RICHARD HERRERA
5/7/91

TRANSMIT TO BUS CONTROLLER

- A COMMAND TO TRANSMIT ELEVEN DATA WORDS TO THE BUS CONTROLLER WILL BE ISSUED EVERY 50 HZ.

RTU ADDRESS	T/R_	SUBADD FIELD	WORD COUNT
00010	1	00001	01011

11 0									11 0	2 0
MOTOR CURRENT	TEMP1	TEMP2	TORQUE1	TORQUE AVE	HALL TACH	LVDT POS	TORQUE R	POS COM CHK	HALLD(1-12)	ANALOG STAT(0-2)

NINE ANALOG INPUTS DIGITIZED BY A/D

ALL NINE WORDS ARE 12 BITS WIDE

1553 BITS 12-15 ARE DON'T CARE BITS

12 BIT DISCRETES

1553 BITS 12-15 ARE DON'T CARE BITS

THREE BIT DISCRETES

1553 BITS 3-15 ARE DON'T CARE BITS

A/D CONVERTER DIGITAL OUTPUT CODING	
ANALOG INPUT VOLTAGE	DIGITAL OUTPUT
+10V	FFFH
0.00 V	100H
-10V	000H

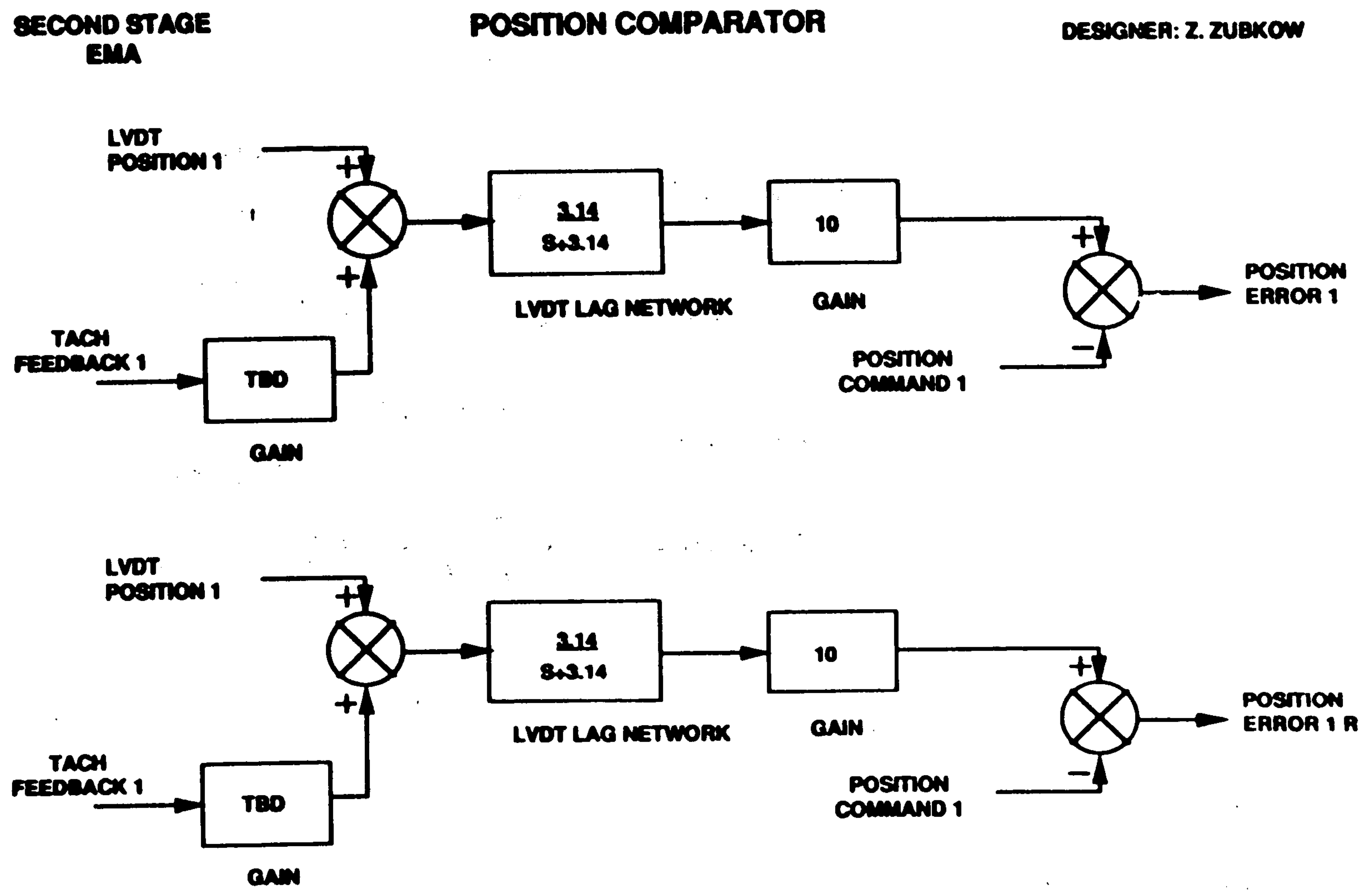
ANALOG LOOP BOARD

DESIGNER: Z. ZUBKOW

MAJOR FUNCTIONS

- POSITION COMPARATOR
  - COMPARES LVDT TO COMMANDED POSITION
- LEAD-LAG
  - CONDITIONS POSITION COMPARATOR SIGNAL INTO TORQUE COMMAND
- LVDT LIMIT DETECT
  - DETECTS IF ACTUATOR POSITION IS AT STROKE LIMIT
- ANALOG STATUS ENCODER
  - ALLOWS 1553 TO MONITOR POSSIBLE ANALOG ERRORS

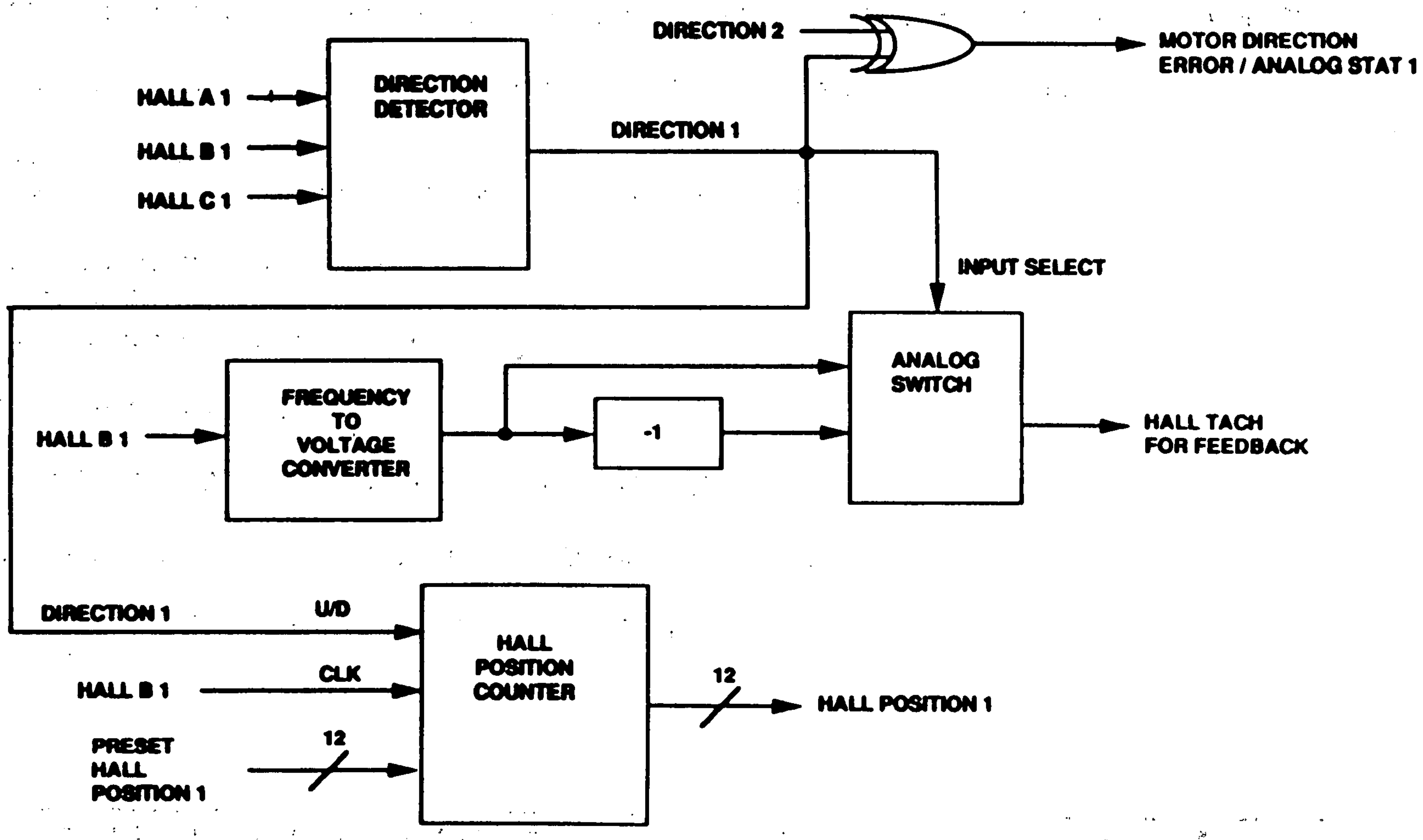
Honeywell


SECOND STAGE EMA
POSITION COMPARATOR
DESIGNER: Z. ZUBKOW
LVDT POSITION 1
TACH FEEDBACK 1
TBD
GAIN
+
+
$\frac{3.14}{S+3.14}$
LVDT LAG NETWORK
10
GAIN
POSITION COMMAND 1
+
−
POSITION ERROR 1
LVDT POSITION 1
TACH FEEDBACK 1
TBD
GAIN
+
+
$\frac{3.14}{S+3.14}$
LVDT LAG NETWORK
10
GAIN
POSITION COMMAND 1
+
−
POSITION ERROR 1 R

SECOND STAGE
EMA

HALL TACH AND POSITION CONVERTER

DESIGNER: Z. ZUBKOW

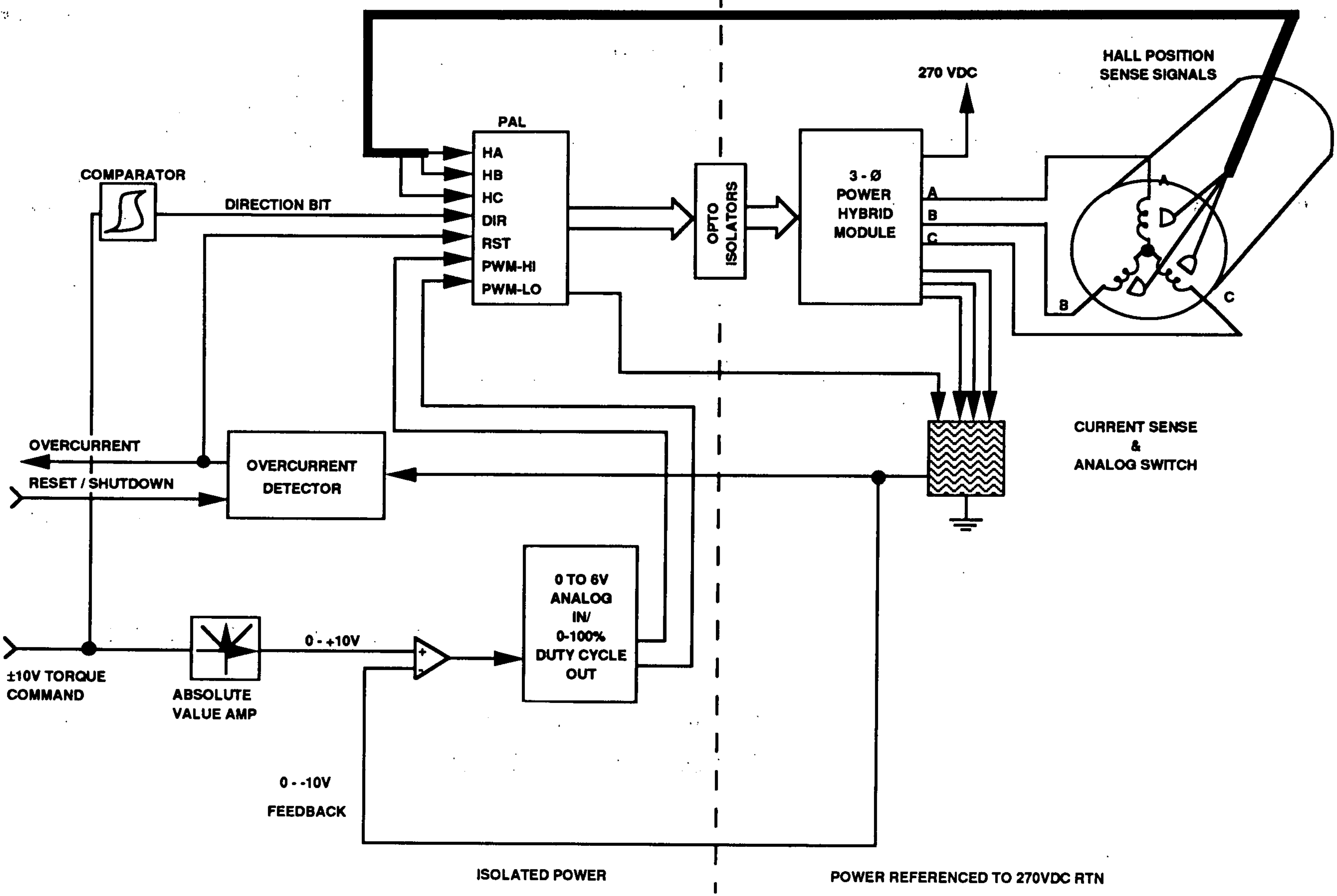


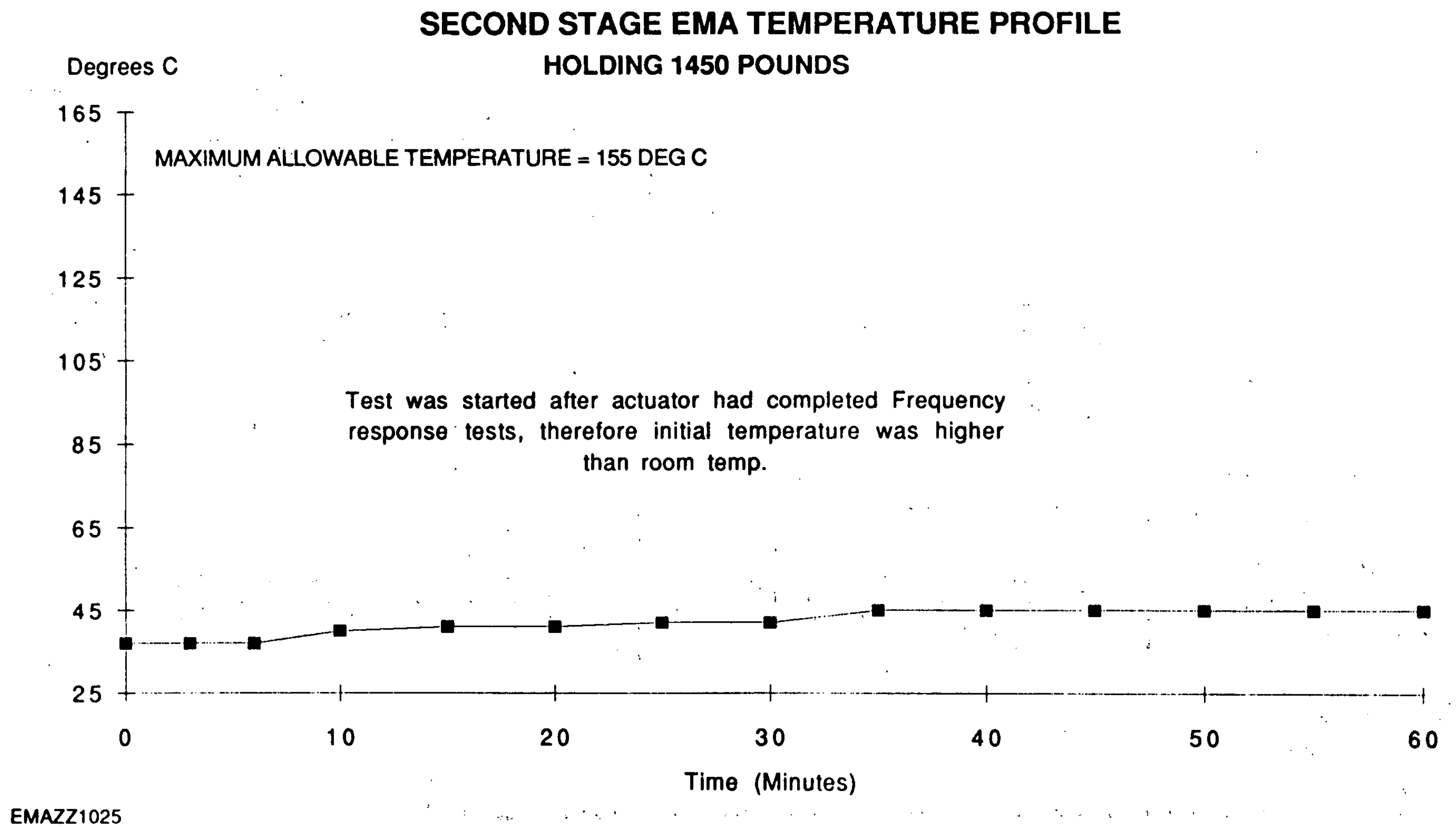
MOTOR CONTROLLER BASELINE

Honeywell

- DESIGN GOAL OF 100 AMPS CONTINUOUS AT 270VDC
- QUAD-REDUNDANT OUTPUT TRANSISTOR DESIGN: 4 X 30 AMPS
- 20 KHZ PULSE-WIDTH-MODULATOR (PWM) FREQUENCY MIN
- SIX-STEP COMMUTATION
- ±10VDC TORQUE COMMAND INPUT:
  0V = NO TORQUE
  1V = 10 AMPS MOTOR CURRENT
- CONTROL ELECTRONICS ELECTRICALLY ISOLATED FROM 270 VDC SUPPLY AND MOTOR
- OVERCURRENT DETECTION FOR EACH OF FOUR OUTPUT TRANSISTOR MODULES
- ACTIVE LOW SHUTDOWN SIGNAL WILL PREVENT SPURIOUS TORQUE APPLICATION AT POWER-UP

Honeywell


PAL
HA
HB
HC
DIR
RST
PWM-HI
PWM-LO
COMPARATOR
DIRECTION BIT
OPTO ISOLATORS
3 - Ø POWER HYBRID MODULE
270 VDC
A
B
C
HALL POSITION SENSE SIGNALS
CURRENT SENSE & ANALOG SWITCH
OVERCURRENT
RESET / SHUTDOWN
OVERCURRENT DETECTOR
0 TO 6V ANALOG IN/ 0-100% DUTY CYCLE OUT
±10V TORQUE COMMAND
ABSOLUTE VALUE AMP
0 - +10V
0 - -10V
FEEDBACK
ISOLATED POWER
POWER REFERENCED TO 270VDC RTN


SECOND STAGE EMA TEMPERATURE PROFILE
HOLDING 1450 POUNDS
Degrees C
165
145
125
105
85
65
45
25
MAXIMUM ALLOWABLE TEMPERATURE = 155 DEG C
Test was started after actuator had completed Frequency response tests, therefore initial temperature was higher than room temp.
0
10
20
30
40
50
60
Time (Minutes)
EMAZZ1025

SESSION V

DEMONSTRATION

SESSION VI

ELA POWER SOURCE SYSTEMS

MARSHALL SPACE FLIGHT CENTER

ENERGY SOURCE TESTING CAPABILITIES

DAVID K. HALL

SEPTEMBER 30, 1992

BATTERIES: BLDG 4475

FLYWHEELS: BLDG 4487

TURBO-ALTERNATORS: BLDG 4656

BATTERIES:

HISTORY

CURRENT TESTING

BLDG. 4475 FACILITIES

MSFC Flight Program History

Program Name	Launch Date	Time of Operation	Regime	Battery Type	Capacity	Cell Manuf.	Battery Manuf.	Remarks
Explorer								Explorer 1 -- First free-world satellite, solar array, and Ni-Cd battery power system
1	2/58	4 mos.	LEO	Ni-Cd		Sonotone		
3	3/58	3 mos.	LEO	Ni-Cd		Sonotone		
4	7/58	4 mos.	LEO	Ni-Cd		Sonotone		
Pegasus								Three satellites with multi-battery SA/Ni-Cd system for large micro-meteroid satellite
1	2/65	3+ yrs.	LEO	Ni-Cd		Gulton ?		
2	5/65	3+ yrs.	LEO	Ni-Cd		Gulton ?		
3	7/65	3+ yrs.	LEO	Ni-Cd		Gulton ?		
Skylab								First manned space station; two SA/Ni-Cd power systems (ATM & OWS) with total capability of >8 kW; operated in parallel; EPS reactivated after more than 4 years in "orbital storage"
ATM	5/73	6 yrs. incl. 4 yrs. storage	LEO	Ni-Cd	20 Ah	GE	MSFC	
OWS	5/73		LEO	Ni-Cd	33 Ah	EPI-J	MDAC-E	
HEAO								Three satellites with multi-battery SA/Ni-Cd power system built by TRW for MSFC; no battery failures
1	8/77	19 mos.	LEO	Ni-Cd		SAFT-Amer.	TRW	
2	11/78	30 mos.	LEO	Ni-Cd		SAFT-Amer.	TRW	
3	9/79	27 mos.	LEO	Ni-Cd		SAFT-Amer.	TRW	

MSFC Flight Program History

Program Name	Launch Date	Time of Operation	Regime	Battery Type	Capacity	Cell Manuf.	Battery Manuf.	Remarks
HST	4/90	30 mos. (active)	LEO	$Ni-H_2$	88 Ah	EPI-J	EPI-J	First reported, non-experimental use of $Ni-H_2$ batteries in LEO; multi-battery SA/$Ni-H_2$ 2.4 kW power system built by LMSC for MSFC; first flight-qualified BPRC (MSFC patent) developed for Ni-Cd batteries before change to $Ni-H_2$
CRRES	7/90	B1-5 mos. B2-15 mos.	MEO	Ni-Cd	15 Ah	GAB	Ford Aerospace	Battery 1 failed after 5 months of operation; battery 2 failed after 15 months of operation; excessive on-orbit overcharge likely major contributor to failures
AXAF-I *	~1999		Elliptical	TBD	30 Ah	TBD	TBD	TRW is the prime contractor for this effort
AXAF-S *	~1999		Polar	TBD	TBD	TBD	TBD	This is an MSFC in-house project

* – *Planned flights*

MSFC Secondary Battery / Cell Testing Summary

Hubble Space Telescope Support:

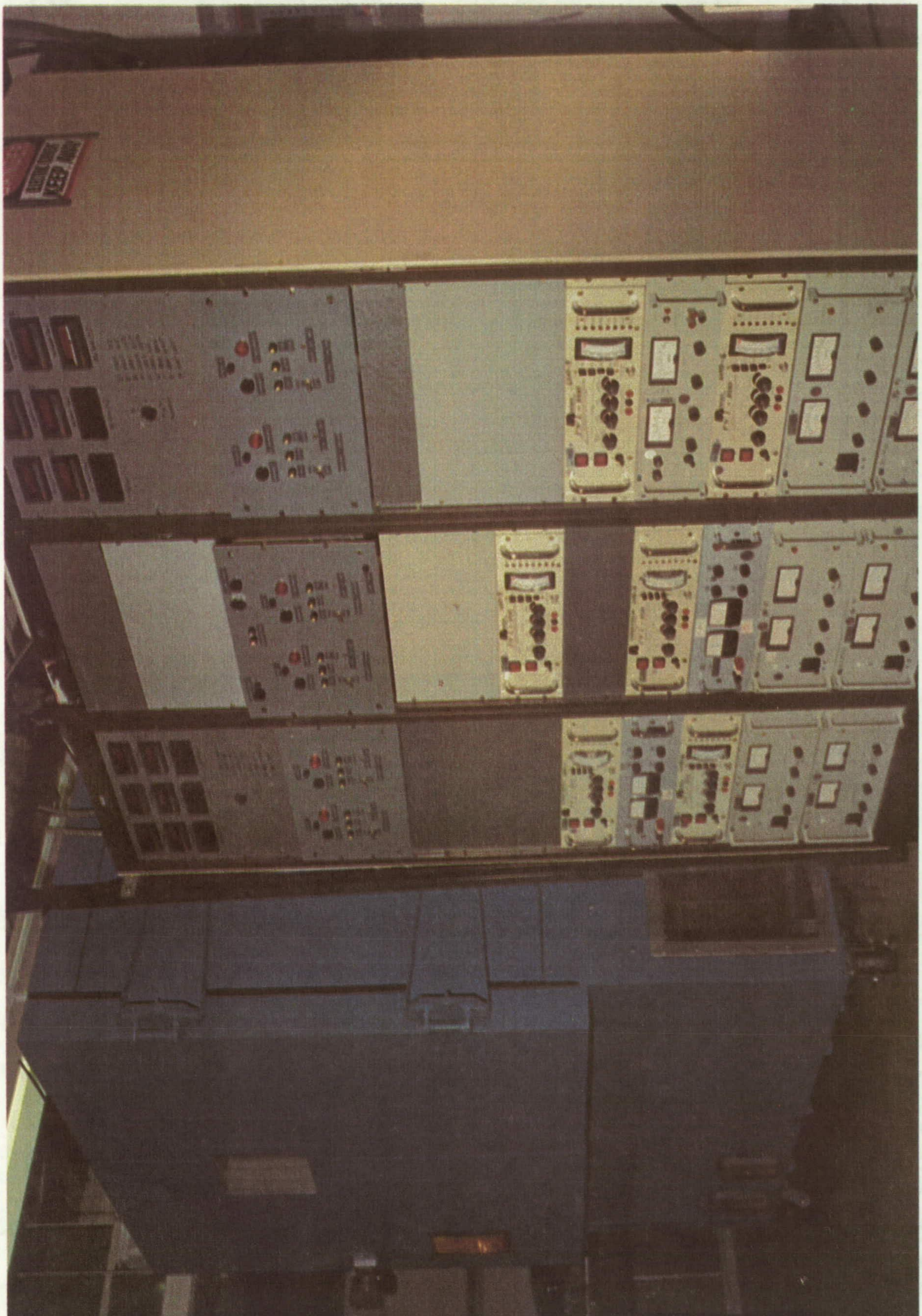
Test Name	Cell Manufacturer	Cell Type	Capacity	Completed Cycles	Regime	%DOD	# of Cells
Type 40 Battery 1 *[1]	EPI-J	Ni-Cd RSN55	55 Ah	23211	LEO	13 - 16	22
Type 40 Battery 2 *[2]	EPI-J	Ni-Cd RSN55	55 Ah	6641	LEO	13 - 16	22
Type 41 *[4]	EPI-J	Ni-Cd RSN55	55 Ah	25891	LEO	13 - 16	22
GE Battery *[3]	GE	Ni-Cd	50 Ah	23872	LEO	13 - 16	22
Six Battery System *[5]	EPI-J	Ni-Cd RSN55-15	55 Ah	21856	LEO	13 - 16	132
Six Four-Cell Packs [6]	EPI-J	Ni-Cd RSN55-15	55 Ah	29850	LEO	13 - 16	24
Fourteen-Cell Pack	EPI-J	$Ni-H_2$ RNH30-1	30 Ah	31000	LEO	6 - 9	14
Three Four-Cell Packs	EPI-J	$Ni-H_2$ RNH90-3	90 Ah	20145	LEO	6 - 9	12
Six Battery System	EPI-J	$Ni-H_2$ RNH90-3	90 Ah	18100	LEO	6 - 9	132
Flight Spare Battery	EPI-J	$Ni-H_2$ RNH90-3	90 Ah	17600	LEO	6 - 9	22

* – *Test has been terminated*
1 – *First cell failure at 14 months*
2 – *First cell failure at 14 months; DPA showed excessive cadmium migration*
3 – *Cell divergence at >14,000 orbits; >100 mV at 19,000 orbits; capacity as low as 30 Ah*
4 – *Cell divergence at >10,000 orbits; capacity as low as 20 Ah*
5 – *Built with reject positive plates; met system reqt. of 36 Ah/battery thru 4 yrs.; had cell short in B3 at 18,300 orbits*
6 – *Cells from flight battery lots; continues to meet system reqt. after 5½ yrs.*

MSFC Secondary Battery / Cell Testing Summary

Other Testing:

Test Name	Cell Manufacturer	Cell Type	Capacity	Completed Cycles	Regime	%DOD	# of Cells
Twelve-Cell Pack	EPI-J	$Ni\text{-}H_2$ RNH35-3	33 Ah	21315	LEO	22	12
Four Four-Cell Packs	EPI-J	$Ni\text{-}H_2$ RNH90-3	90 Ah	58	Elliptical	30	16
Reconditioning	EPI-J	$Ni\text{-}H_2$ RNH90-3	90 Ah	5500	LEO	30	8
Parametric Tests	EPI-J	Ni-MH RMH10-1	10 Ah				24
AXAF-S Ni-MH	EPI-J	Ni-MH RMH10-1	10 Ah		LEO		8
SEDS / UAH	EPI-J	Ni-MH RMH10-1	10 Ah		LEO		22
SEDS Satellite	EPI-J	Ni-MH RMH10-1	10 Ah		LEO		22



BATTERY THERMAL CHAMBER, BUILDING 4475

ORIGINAL PAGE
COLOR PHOTOGRAPH

FLYWHEELS:

BLDG 4487;

TWO CONTAINMENT VAULTS

ON-GOING CMG TESTING

LARGE FLYWHEEL CONTAINMENT VAULT, BUILDING 4487

SMALL FLYWHEEL CONTAINMENT VAULT, BUILDING 4487

TURBO-ALTERNATORS:

BLDG 4656;

HIGH PRESSURE HELIUM

HIGH PRESSURE NITROGEN

3000 PSI HYDRAULICS

JOHNSON CONTROLS BATTERY GROUP INC.

BIPOLAR LEAD/ACID BATTERY

NASA ELECTRICAL ACTUATION

TECHNOLOGY BRIDGING

WORKSHOP

AT

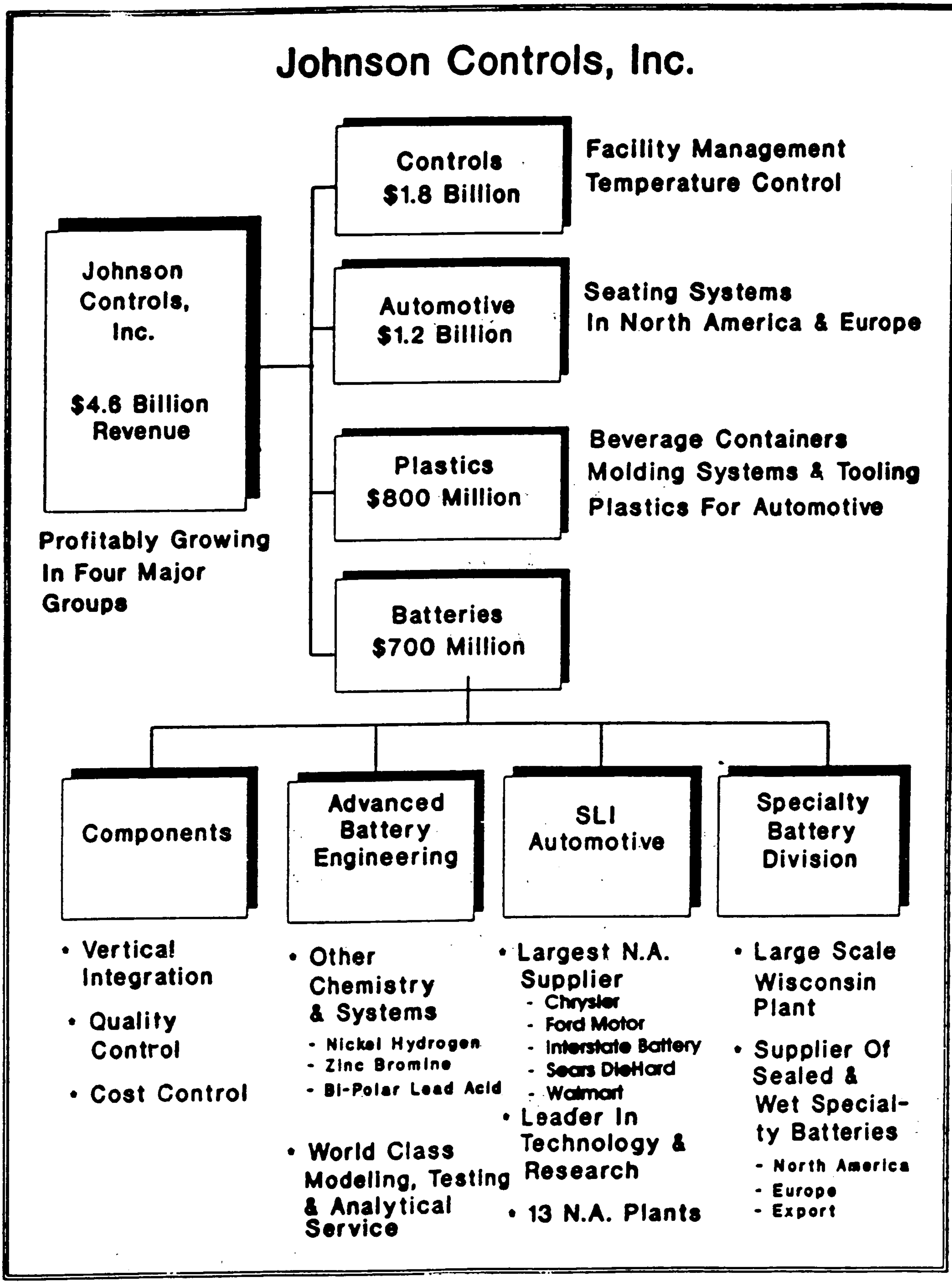
MARSHALL SPACE AND FLIGHT CENTER
HUNTSVILLE, ALABAMA

SEPTEMBER 30, 1992

PRESENTED BY

WILLIAM O. GENTRY
DOUGLAS C. PIERCE

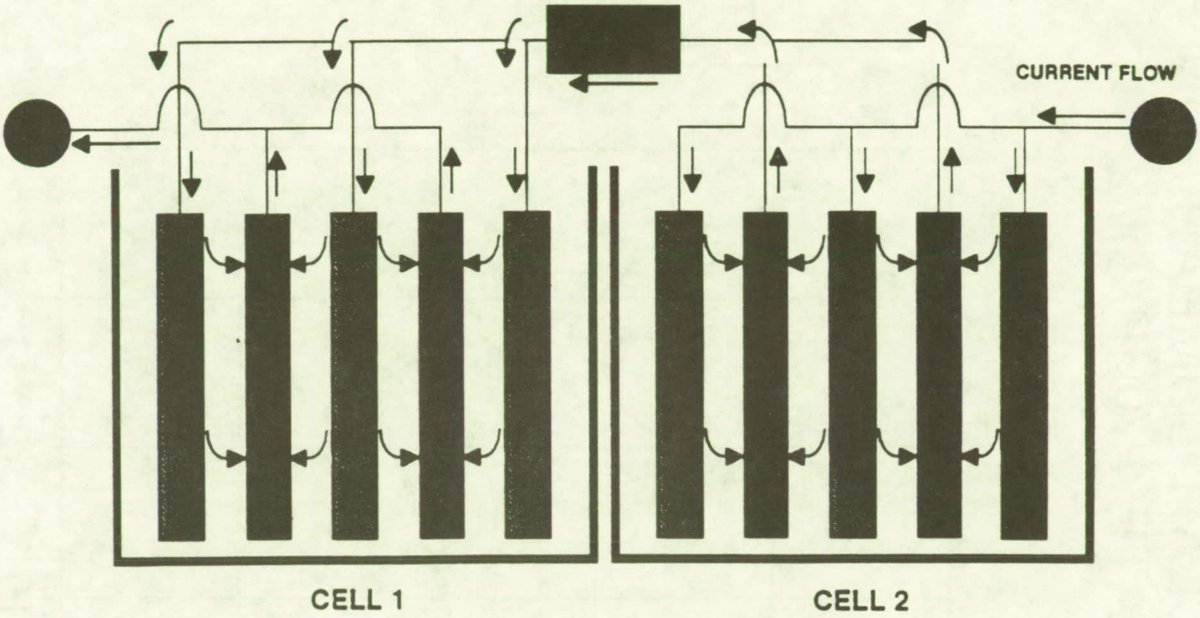
JOHNSON CONTROLS


Johnson Controls, Inc.
Controls
$1.8 Billion
Facility Management
Temperature Control
Johnson Controls, Inc.
$4.6 Billion Revenue
Automotive
$1.2 Billion
Seating Systems
In North America & Europe
Plastics
$800 Million
Beverage Containers
Molding Systems & Tooling
Plastics For Automotive
Profitably Growing In Four Major Groups
Batteries
$700 Million
Components
• Vertical Integration
• Quality Control
• Cost Control
Advanced Battery Engineering
• Other Chemistry & Systems
- Nickel Hydrogen
- Zinc Bromine
- Bi-Polar Lead Acid
• World Class Modeling, Testing & Analytical Service
SLI Automotive
• Largest N.A. Supplier
- Chrysler
- Ford Motor
- Interstate Battery
- Sears DieHard
- Walmart
• Leader In Technology & Research
• 13 N.A. Plants
Specialty Battery Division
• Large Scale Wisconsin Plant
• Supplier Of Sealed & Wet Specialty Batteries
- North America
- Europe
- Export

MONOPOLAR AND BIPOLAR CURRENT PATH SCHEMATICS

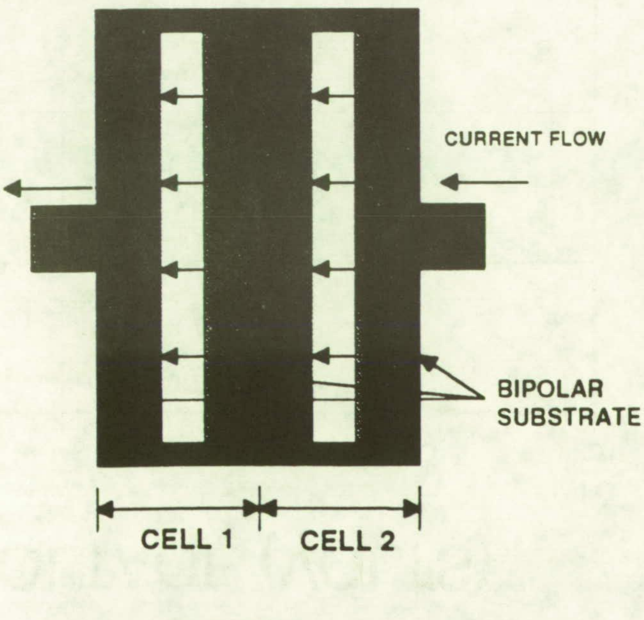
MONOPOLAR CONFIGURATION

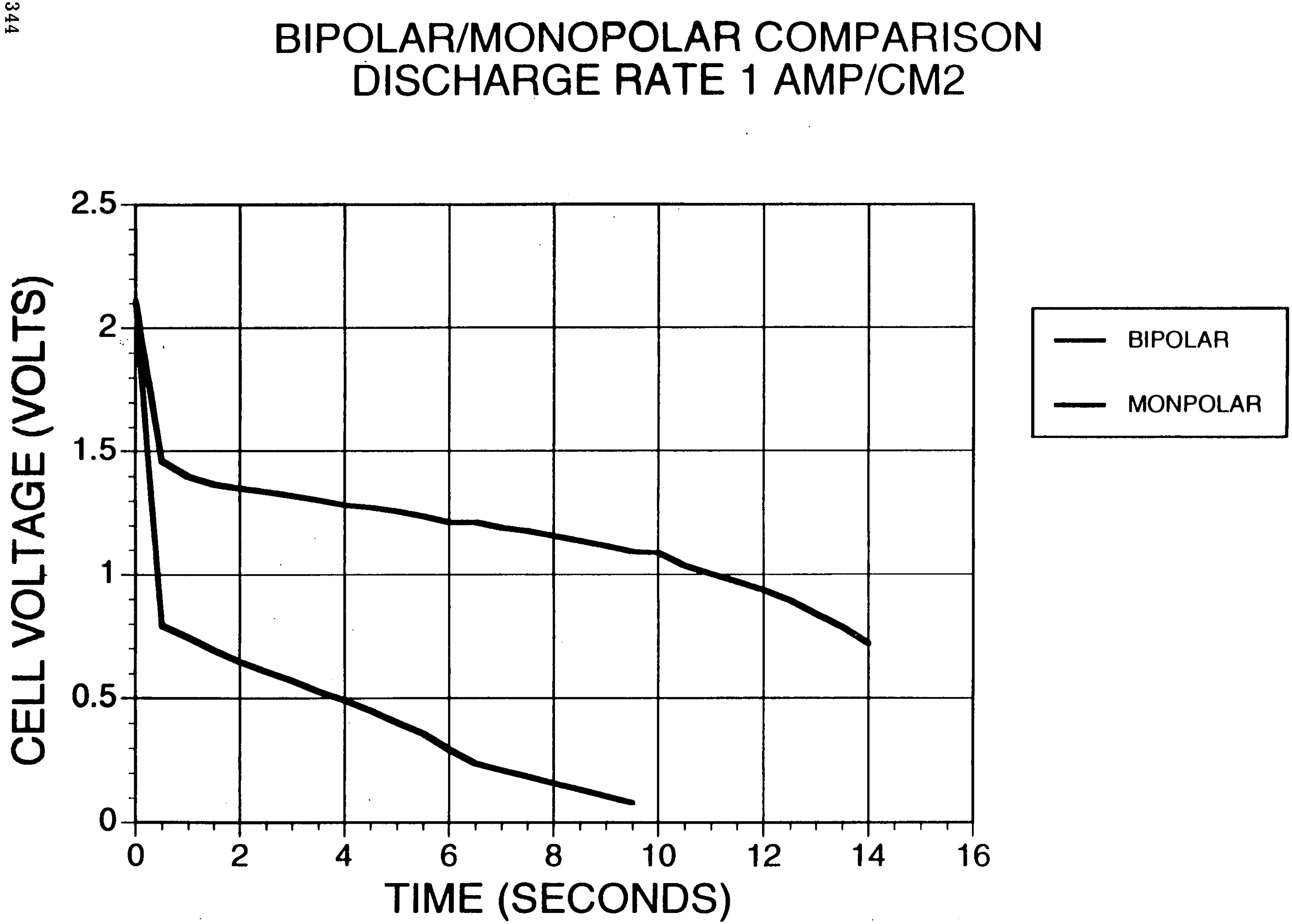
TWO CELL / 4-VOLT SYSTEM



BIPOLAR CONFIGURATION

TWO CELL / 4-VOLT SYSTEM




BIPOLAR/MONOPOLAR COMPARISON
DISCHARGE RATE 1 AMP/CM2
CELL VOLTAGE (VOLTS)
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
TIME (SECONDS)
BIPOLAR
MONPOLAR

JCBGI
BIPOLAR LEAD/ACID ADVANTAGES

- PROVEN LEAD-ACID CHEMISTRY

- SEALED, MAINTENANCE FREE OPERATION

- SHORTER CURRENT PATH
    - LOWER INTERNAL BATTERY RESISTANCE

- REDUCED WEIGHT AND VOLUME

- SUBSTANTIAL POWER ADVANTAGES OVER MONOPOLAR
    - ≈100% INCREASE IN POWER DENSITY FOR QUASI
    - ≈140% INCREASE IN POWER DENSITY FOR TRUE
    - ≈75% INCREASE IN SPECIFIC POWER FOR QUASI
    - ≈150% INCREASE IN SPECIFIC POWER FOR TRUE

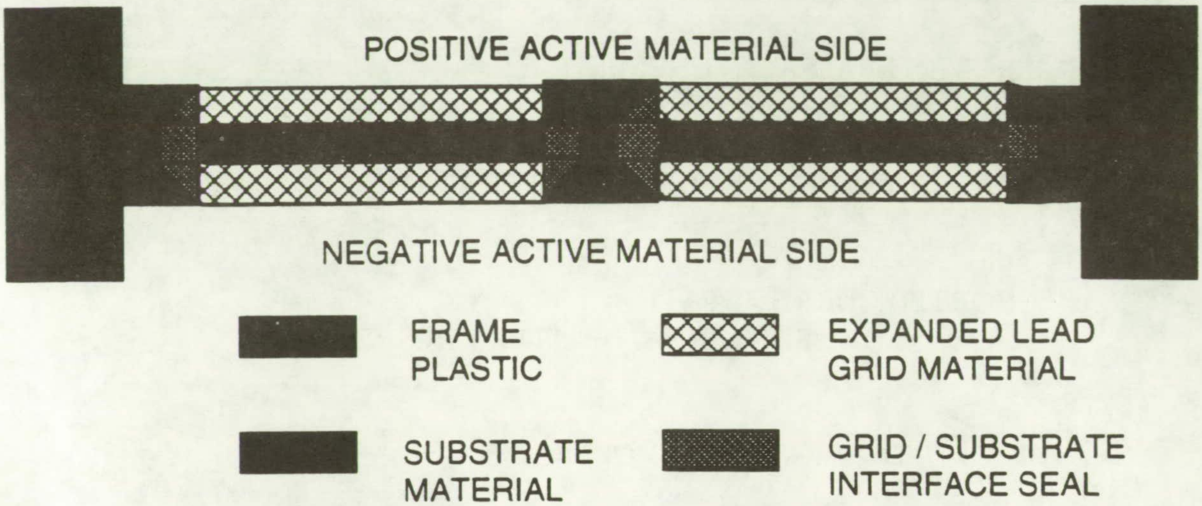
- MEANS OF VARYING STACK VOLTAGE WITHOUT RE-TOOLING

- PACKAGING FLEXIBILITY

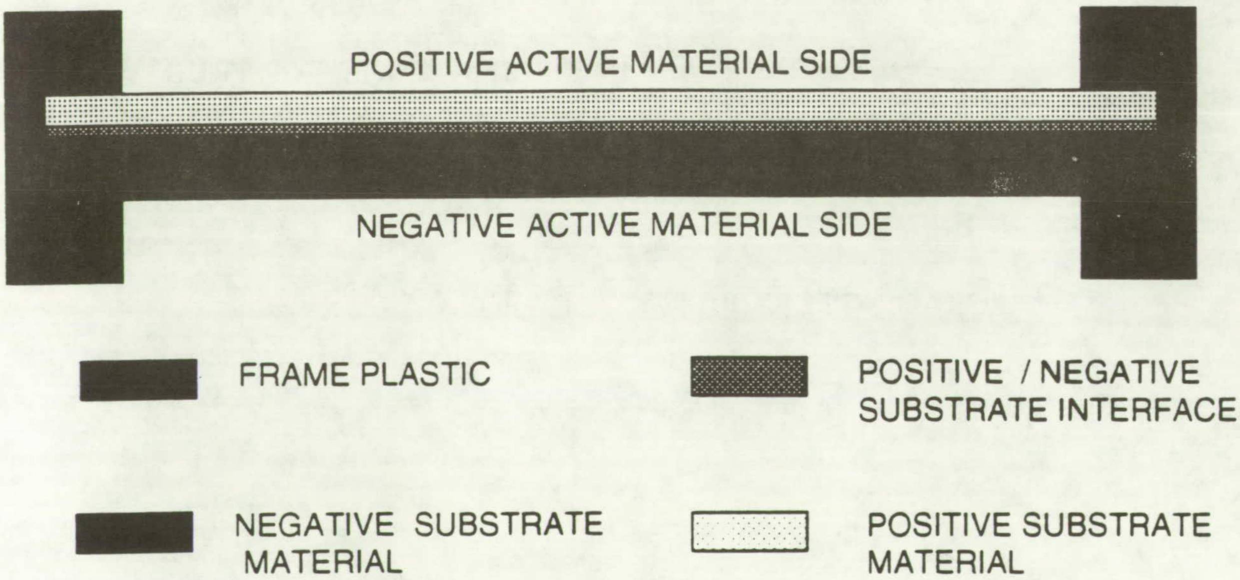
JOHNSON CONTROLS

BIPOLAR BATTERY COMPARISON

FOLDED BIPOLAR PLATE



TRUE BIPOLAR PLATE



TRUE/QUASI BIPOLAR COMMON POINTS

- LEAD-ACID TECHNOLOGY
- FRAME DESIGN
- ASSEMBLY TECHNIQUES
    - IR WELDING
    - VIBRATION WELDING
- ACTIVE MATERIAL
- SEPARATOR
- FORMATION AND ACID FILL TECHNIQUES
- TERMINATION DESIGN
- INITIAL CONTAINMENT DESIGN

JOHNSON CONTROLS

TRUE/QUASI BIPOLAR DIFFERENCES

- INSERT MATERIAL
  - QUASI- FOLDED LEAD GRID ELECTRODE
  - TRUE- COMPOSITE TRUE BIPOLAR SUBSTRATE
- MANUFACTURABILITY
- FAILURE MODES
  - QUASI- GRID CORROSION, FOLD SEAL LEAK
  - TRUE- ACTIVE MATERIAL DEGRADATION
- CELL SPACING AND CELL SIZE WILL BE SMALLER IN TRUE BIPOLAR
- HIGHER PERFORMANCE CHARACTERISTICS IN TRUE BIPOLAR
- SMALLER MASS, SMALLER VOLUME

JOHNSON CONTROLS

JCBGI QUASI BIPOLAR STATUS

- CURRENTLY HAVE TWO DIFFERENT SIZE PLATES: 520, 940 cm^2

- DEMONSTRATED 30 SEC AVERAGE POWER OF 210 W/kg at 80% DOD

- DEMONSTRATED HIGH SPECIFIC POWER: 1.5 kW/kg FOR 12 SECONDS

- DEMONSTRATED OVER 100 CYCLES AT TWO INDEPENDENT LOCATIONS

- BUILT NINE 430 VOLT BATTERY STRINGS

- INCREASED PRODUCTION FROM FIFTY 12 VOLT BATTERIES PER YEAR TO THIRTY 40 VOLT BATTERIES PER WEEK

- INCREASED FORMATION SUCCESS RATE FROM 10% TO 80%

- CONTAMINATION DURING PROCESSING HAS CAUSED CYCLE LIFE PROBLEMS

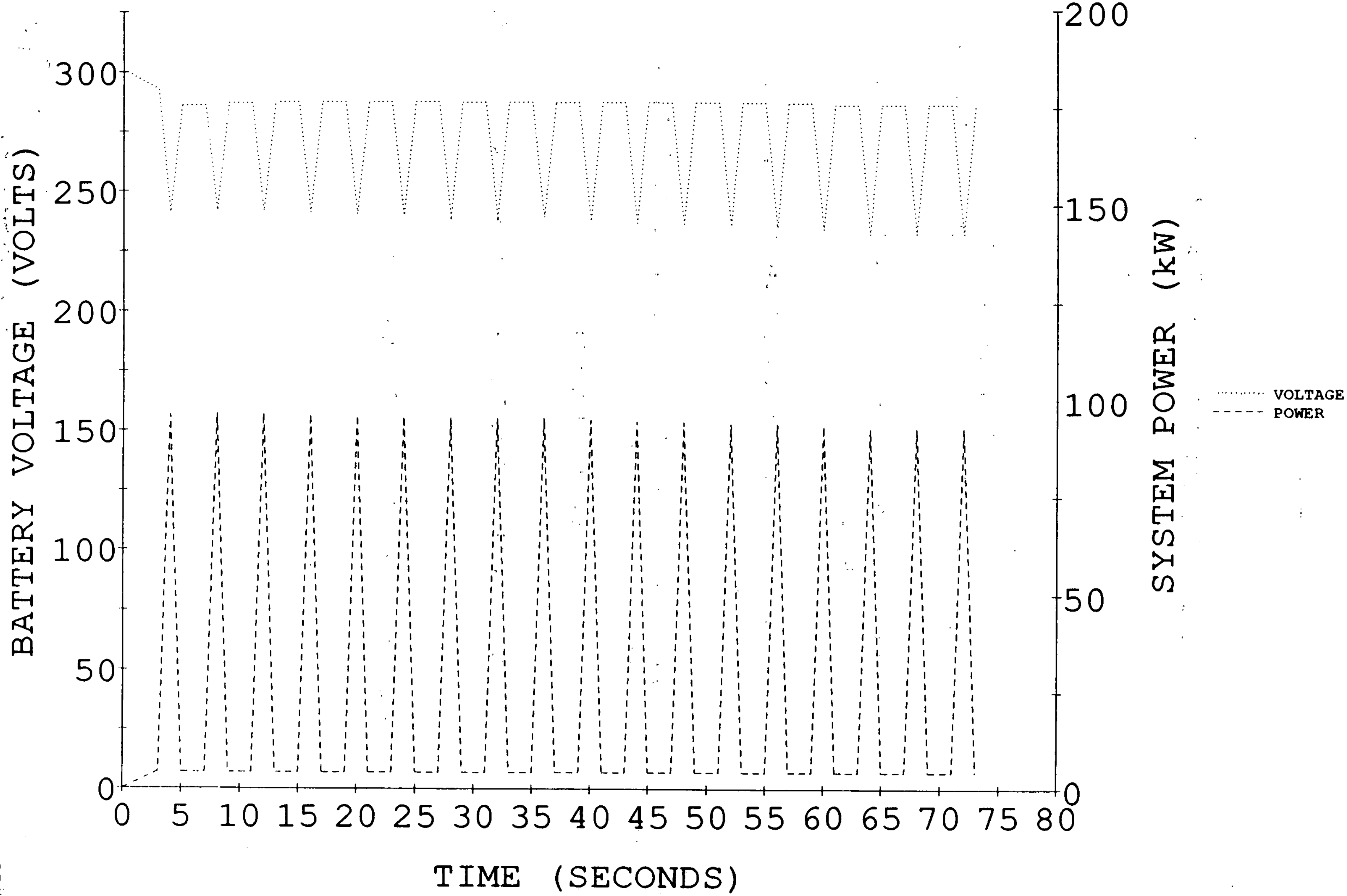
JOHNSON CONTROLS

POROSITY IN PLASTIC COMPOSITES

- HIGH FILLER LOADINGS LEAD TO POROSITY
- DIFFICULT TO PREVENT
- PROCESS/PRODUCT INVESTIGATIONS
    - RESIN IMPREGNATION OF POROUS COMPOSITES
    - COMPRESSION MOLDING IMPROVEMENTS
    - LOWER FILLER LOADINGS THROUGH BETTER DISPERSION
    - HIGHER CONDUCTIVITY FILLERS

JOHNSON CONTROLS

JOHNSON CONTROLS QUASI BIPOLAR BATTERY
MSFC DISCHARGE



JCBGI QUASI BIPOLAR FUTURE WORK

- ELIMINATE MATERIAL PROBLEMS THAT HAVE CAUSED CYCLE LIFE PROBLEMS THROUGH HIGH LEVELS OF CONTAMINATION

- DEMONSTRATE 100 CYCLE CAPABILITY ON 20 CELL BATTERY AND A 200 CELL STRING

- OVERCOME CELL INCONSISTENCIES WHICH LIMIT BATTERY PERFORMANCE

- DEVELOP A RECHARGE REGIME THAT WILL ENSURE UNIFORM CHARGING OF HIGH VOLTAGE STRINGS

    - LARGER DATA BASE IS NEEDED

- REFINE ACID MANAGEMENT SYSTEM TO PERMIT A TOTALLY CLOSED SYSTEM

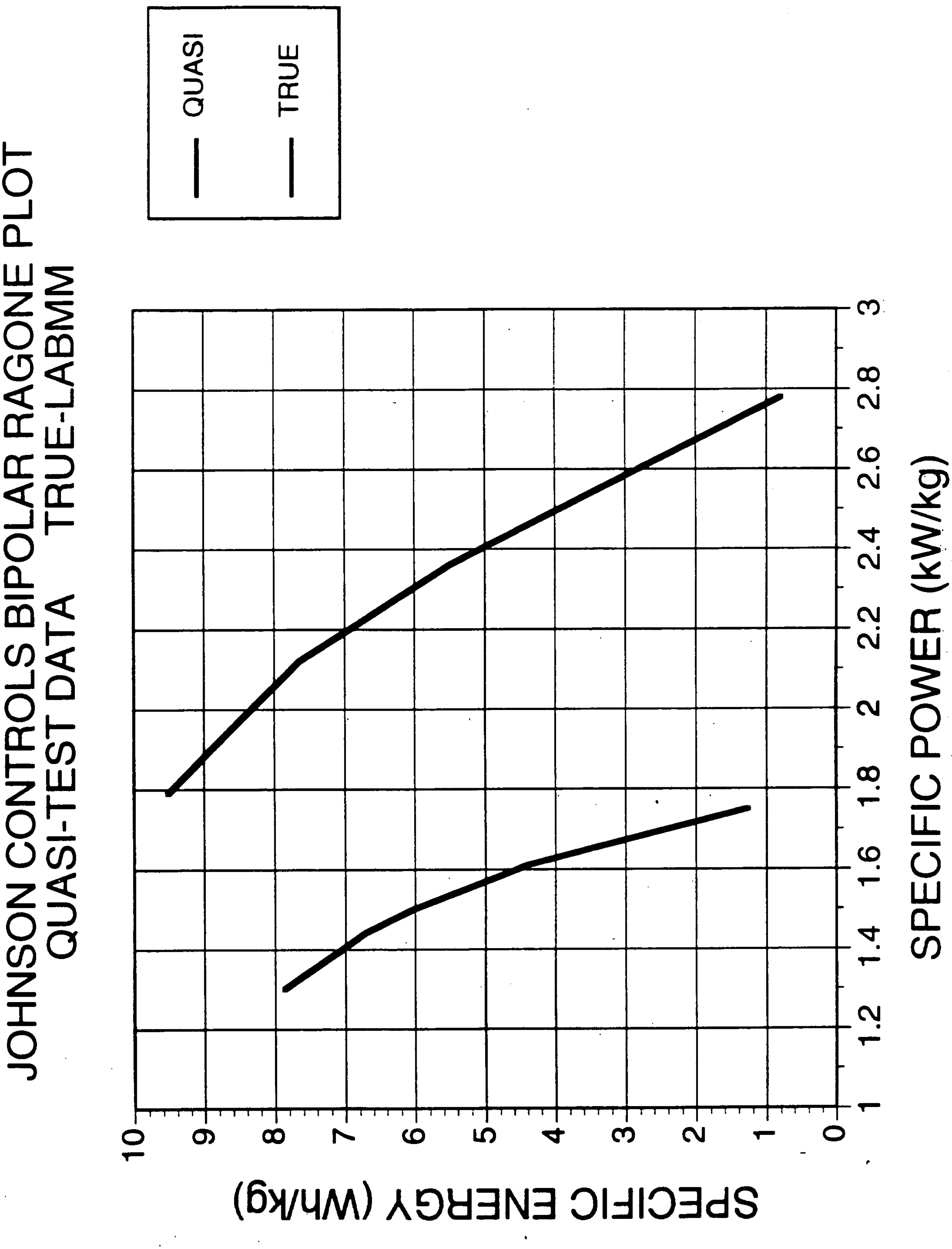
- IMPLEMENT RECENT DESIGN MODIFICATIONS

JOHNSON CONTROLS

TRUE BIPOLAR ADVANTAGES

- LOWER INTERNAL RESISTANCE THAN QUASI BIPOLAR
- SHORTER, MORE UNIFORM CURRENT PATH
- LARGER ACTIVE AREA
- SUBSTANTIAL VOLUME AND WEIGHT SAVINGS
- HIGHER POWER APPLICATIONS QUASI
- LOWER LEAD CONTENT: LOWER MASS
- IMPROVED MANUFACTURABILITY
- ELIMINATES PRESENT FAILURE MECHANISMS
    - LEAD GRID CORROSION ON CHARGING
    - FOLD SEAL LEAKS
    - CONTAMINATION

JOHNSON CONTROLS


JOHNSON CONTROLS BIPOLAR RAGONE PLOT
QUASI-TEST DATA TRUE-LABMM
QUASI
TRUE
SPECIFIC ENERGY (Wh/kg)
SPECIFIC POWER (kW/kg)
0
1
2
3
4
5
6
7
8
9
10
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3

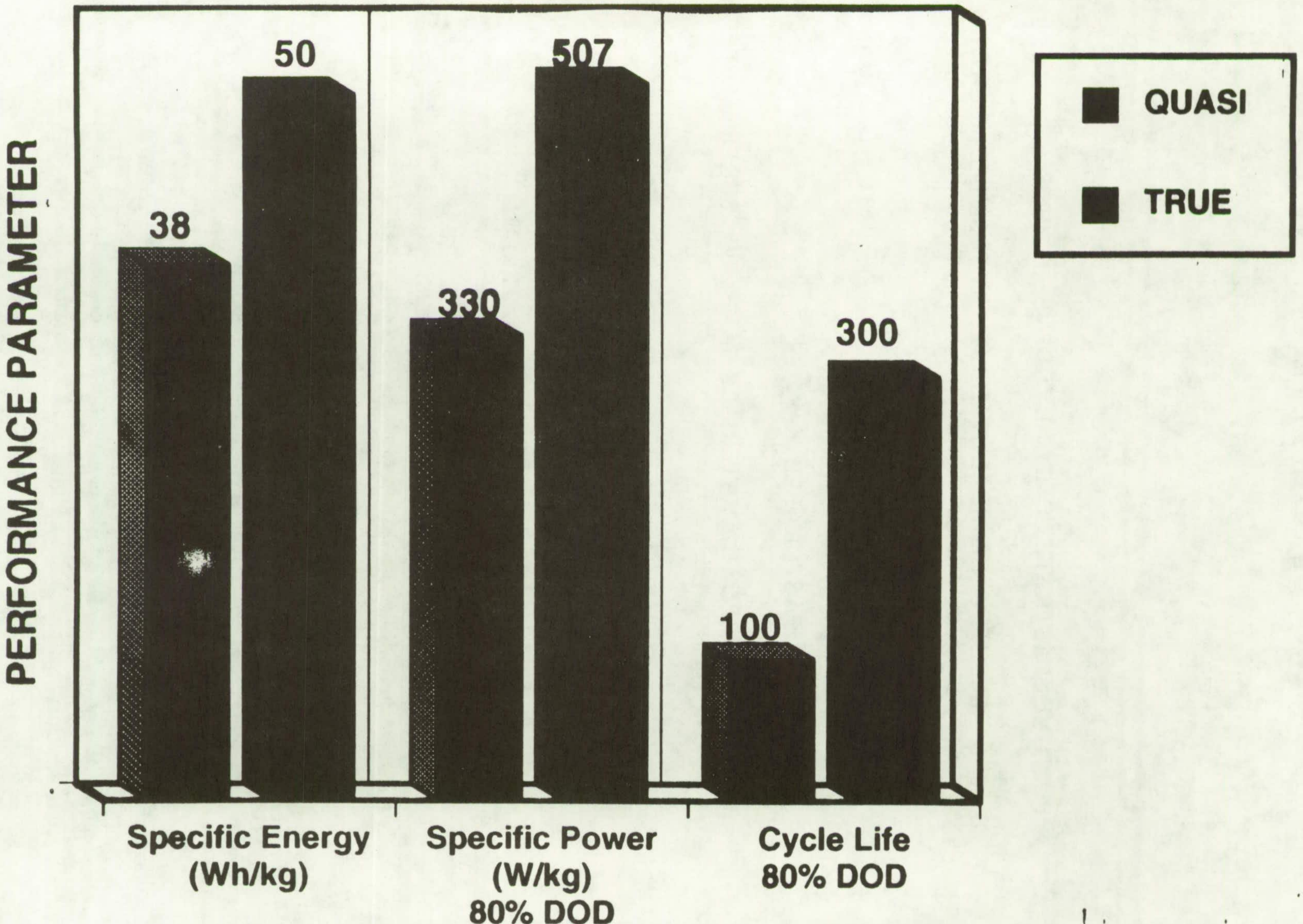
TRUE BIPOLAR DEVELOPMENT

- POSITIVE SUBSTRATE COMPONENT DEVELOPMENT
    - ELECTROCHEMICAL STABILITY AT POSITIVE POTENTIALS
    - HIGH CONDUCTIVITY
    - NON-POROUS
    - MANUFACTURABLE
    - HUNDREDS OF MATERIALS HAVE BEEN SCREENED: FEW QUALIFIED

- POSITIVE SUBSTRATE COMPONENTS HAS BEEN IDENTIFIED
    - IMPROVE CONDUCTIVITY OF MATERIAL
    - OPTIMIZE COMPOUNDING PROCEDURES

JOHNSON CONTROLS

BIPOLAR LEAD-ACID PERFORMANCE COMPARISON



9/9/92

TRUE BIPOLAR DEVELOPMENT

- NEGATIVE SUBSTRATE MATERIAL ALREADY IDENTIFIED
  - STABLE AT NEGATIVE POTENTIALS
  - HIGHLY CONDUCTIVE
  - NON-POROUS
  - EASY TO MANUFACTURE
  - NOT STABLE AT POSITIVE POTENTIALS

- NO MATERIAL HAS BEEN IDENTIFIED THAT IS STABLE AT BOTH ELECTRODES

- INTERFACE BETWEEN POSITIVE AND NEGATIVE
  - PROTECT NEGATIVE FROM POSITIVE POTENTIAL AND POSITIVE FROM NEGATIVE POTENTIAL
  - MAINTAIN CONDUCTIVITY WITH EACH SIDE

JOHNSON CONTROLS

JCBGI TRUE BIPOLAR DEVELOPMENT FOR WPAFB

- A 270 VOLT BATTERY SYSTEM IS TARGETED FOR THE MORE ELECTRIC AIRCRAFT

- DEVELOP A LEAD-ACID TRUE BIPOLAR SUBSTRATE WITH THE FOLLOWING GOALS

    - 0.025" TOTAL SUBSTRATE THICKNESS

    - $\leq$ 2 ohm-cm RESISTIVITY

    - 400 cm^2 ACTIVE AREA

    - $\leq$ 150 mg/cm^2 AREA DENSITY

- DELIVER TWO INTERIM TRUE BIPOLAR BATTERIES. A 54 VOLT BATTERY IS SCHEDULED FOR DELIVERY IN AUGUST 1994.

JOHNSON CONTROLS

BMET PERFORMANCE REQUIREMENTS
BIPOLAR BATTERY SPECIFICATIONS
Near Term Projections (within 5 years)
330 Volt Battery Systems

REQUIREMENTS MET	BATTERY DIMENSIONS	BATTERY VOLUME	BATTERY WEIGHT	W/kg	W/cm3	W-hr/kg	W-hr/cm3
Main Engine Starting APU Starting Hybrid Emergency	17.6"x15.5"x15.5"	2.45 ft3	450 lbs	747.9	2.2	12.25	0.036
Main Engine Starting Ground Power Emergency Power APU Starting Hybrid Emergency							
Scenario 1 30 minute ground power capacity	27.4"x19.7"x19.7"	6.15 ft3	1000 lbs	62.2	0.16	31.08	0.081
Scenario 2 45 minute ground power capacity	36.2"x19.7"x19.7"	8.13 ft3	1349 lbs	46.1	0.12	34.56	0.092
APU Starting	16.5"x4.33"x4.33"	0.18 ft3	33 lbs	705.0	2.1	11.75	0.036

WPAFB TRUE BIPOLAR PROGRESS

- PERFORMANCE MODELING
- CONDUCTIVE FILLER DEVELOPMENT
- POROSITY CONTINUES TO BE A PROBLEM
- ORDERED AN ENHANCED COMPRESSION MOLD
- RECEIVED CONDUCTIVE FILLER IN PROTOTYPE SIZED BATCHES
    - ALLOWS FOR LARGER COMPOUNDING TRIALS
    - CAN BE USED IN NEW COMPRESSION MOLD
- INTERFACE MATERIAL HAS BEEN IDENTIFIED

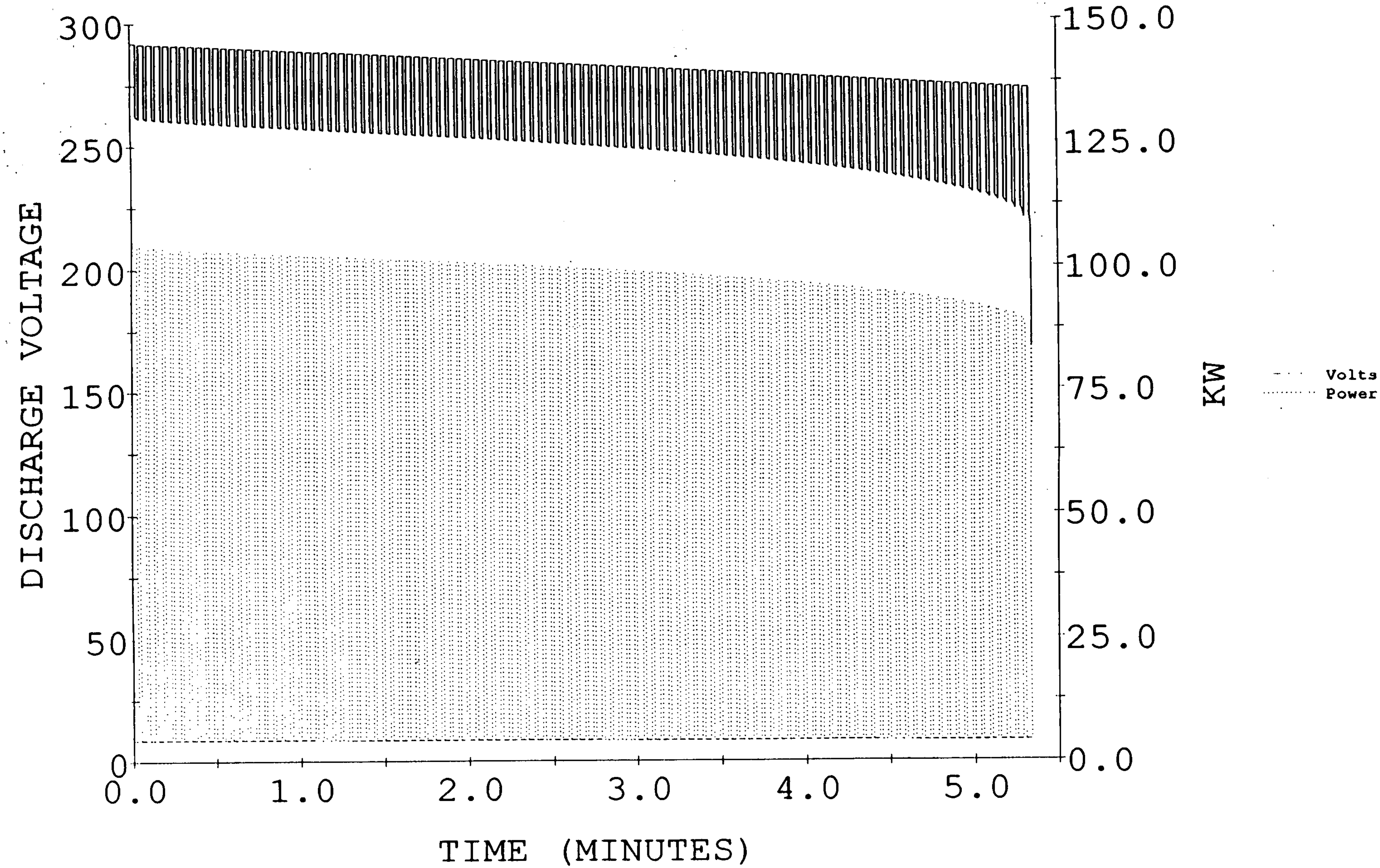
JOHNSON CONTROLS

WPAFB NEXT STEPS

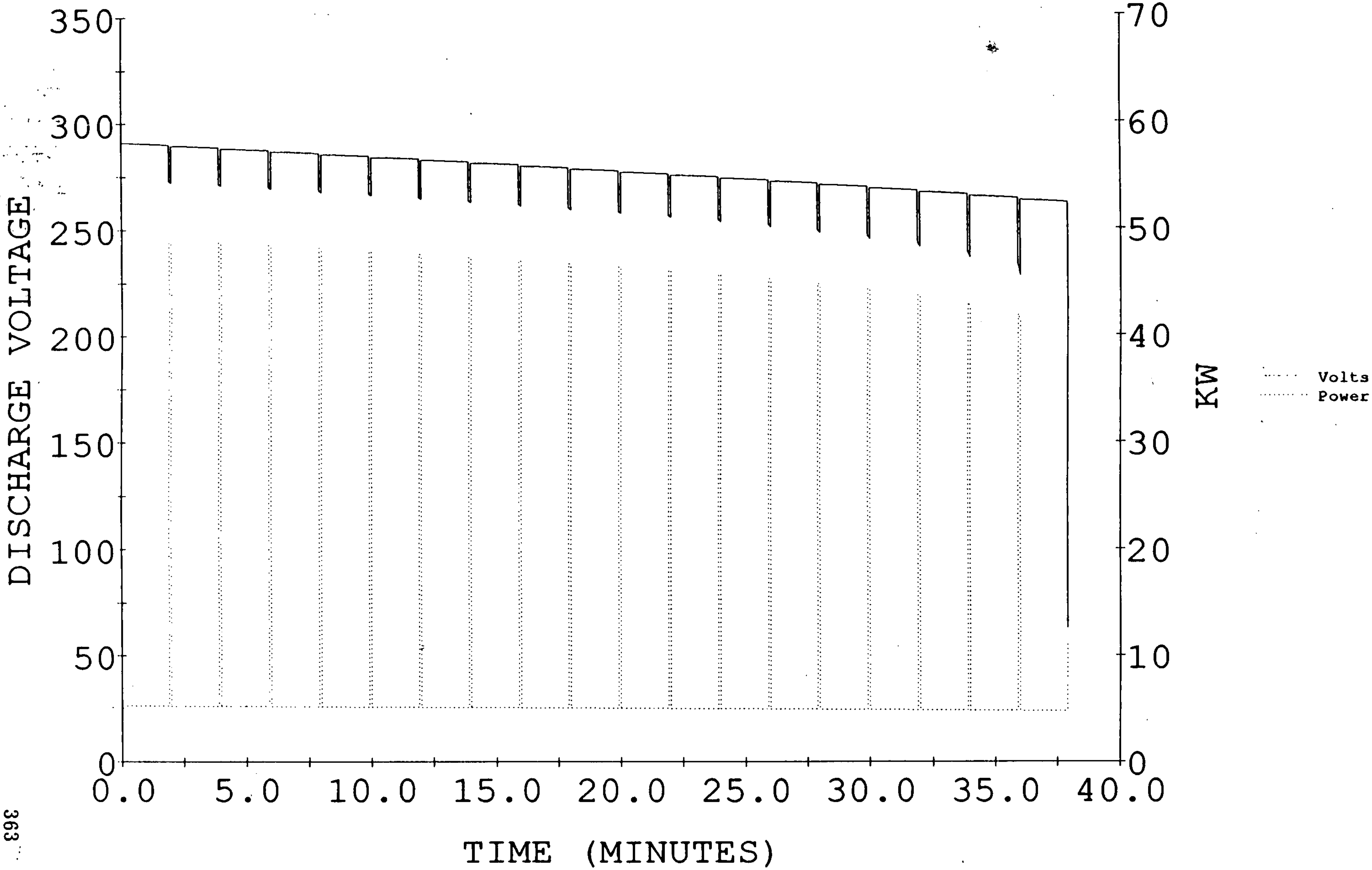
- STATISTICALLY DESIGNED COMPOUNDING TRIALS TO OPTIMIZE LOADING LEVEL
- REFINE COMPOUNDING PROCEDURES
- TEST DIFFERENT PLASTIC RESINS
- USE MATERIAL FROM COMPOUNDING TRIALS IN COMPRESSION MOLD
- STABILITY TEST TO QUALIFY NEW FORMULATIONS

JOHNSON CONTROLS

LABMM MODEL SIMULATION
TRUE BIPOLAR BATTERY, 7 20-CELL MODULES
15 A FOR 2 SEC, 400 A FOR 1 SEC
20 DEGREES C, 6/10/92



LABMM SIMULATION
TRUE BIPOLAR BATTERY, 7 20-CELL MODULES
18 A FOR 114 SEC, 180 A FOR 6 SEC
20 DEGREES C, 6/10/92



Advanced Battery Characteristics
for ELA Applications

Johnson Controls Bipolar Lead/Acid Battery

	QUASI BIPOLAR	TRUE BIPOLAR
Output Voltage	1.0-2.15 V/cell	1.0-2.15 V/cell
Nominal Voltage	2 V/cell	2 V/cell
Plateau Voltage	1.2-2.1 V/cell	1.2-2.1 V/cell
Voltage Rise Time (delay)	NA	NA
Average Current	as needed	as needed
Maximum Pulse Current	1000 amps; 15 sec	1500 amps; 20 sec
Rated Discharge Current	0 to 1000 amps	0 to 1500 amps
Current Density	max 1.2 A/cm^2	max 1.5 A/cm^2
Specific Energy (Wh/kg)	38	44
Inverse Power Density (L/kW)	0.253	0.088
Maximum Pulse Power	1.2 kW/cell; 15 sec	1.8 kW/cell; 20 sec
Transient Response Time	NA	NA
Specific Power (kW/kg)	1.5 to 2.0	3.0 to 3.5
Total Energy Storage Capacity	90 Wh/cell	120 Wh/cell
Cycle Life	100+	300+
Open Circuit Voltage	2.15 V/cell	2.15 V/cell
Safety Issues	Lead;Acid	Lead;Acid
Thermal Operating Range (C)	-30 to +65	-30 to +65
Charging Time; Retention	3 hours; weeks	2 hours; weeks
Capacity	15 Ah; $940cm^2$	20 Ah; $1000cm^2$
Mass	0.85 kg/cell	0.60 kg/cell
Stage of Development	6	3

JOHNSON CONTROLS

ELECTROMECHANICAL ACTUATION

POWER SOURCE STUDY

SILVER OXIDE - ZINC

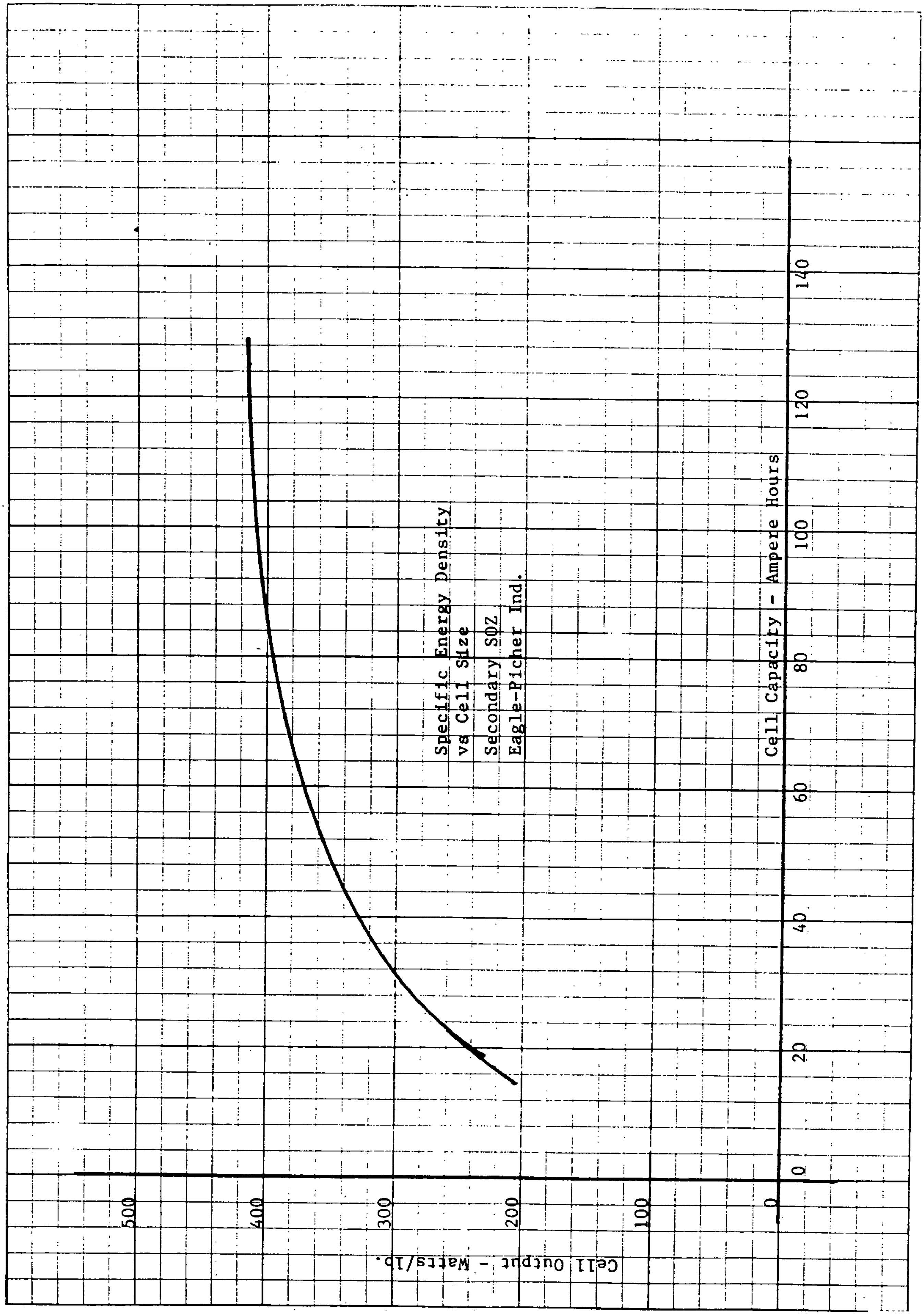
SECONDARY

RESERVE PRIMARY

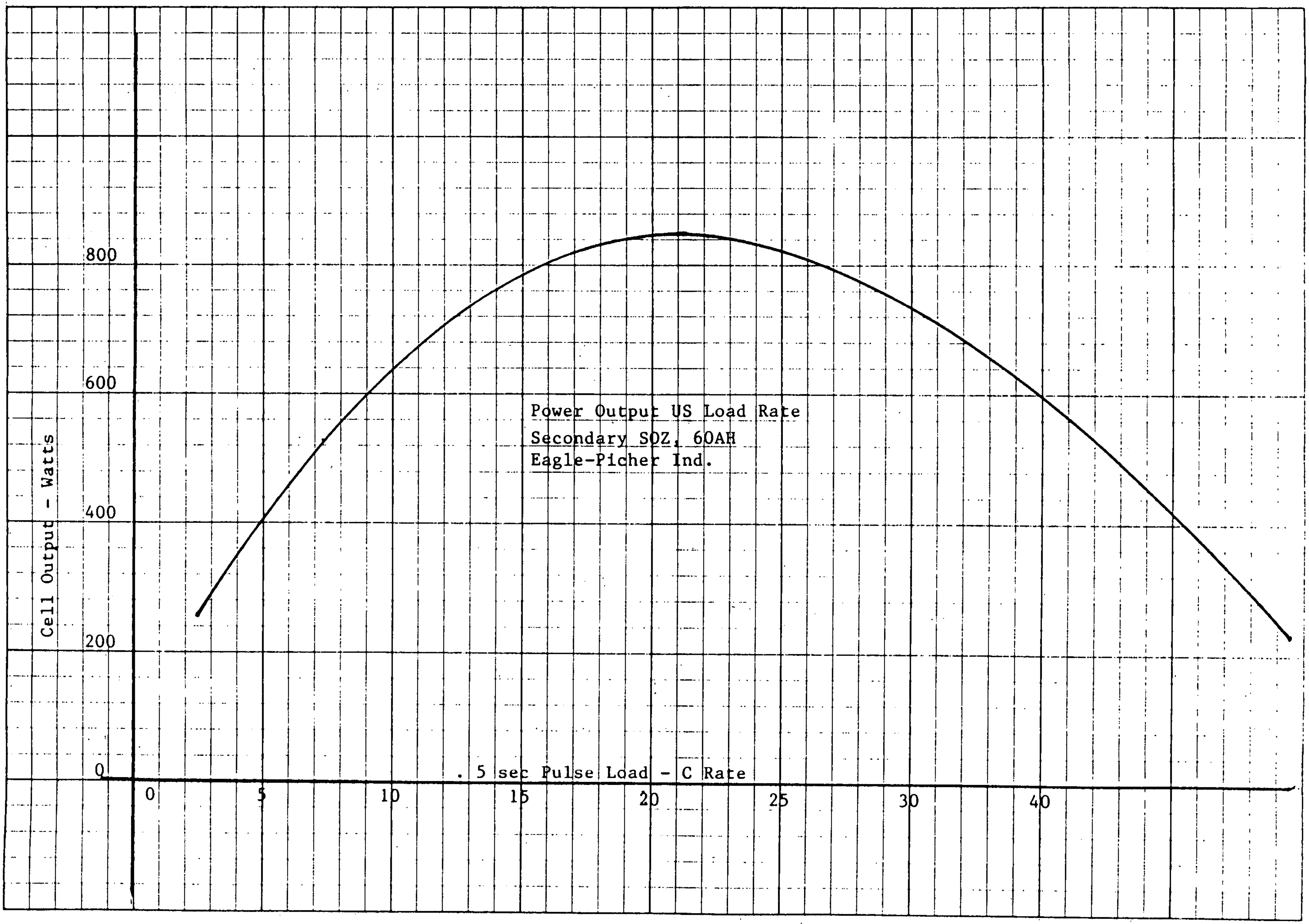
BIPOLAR

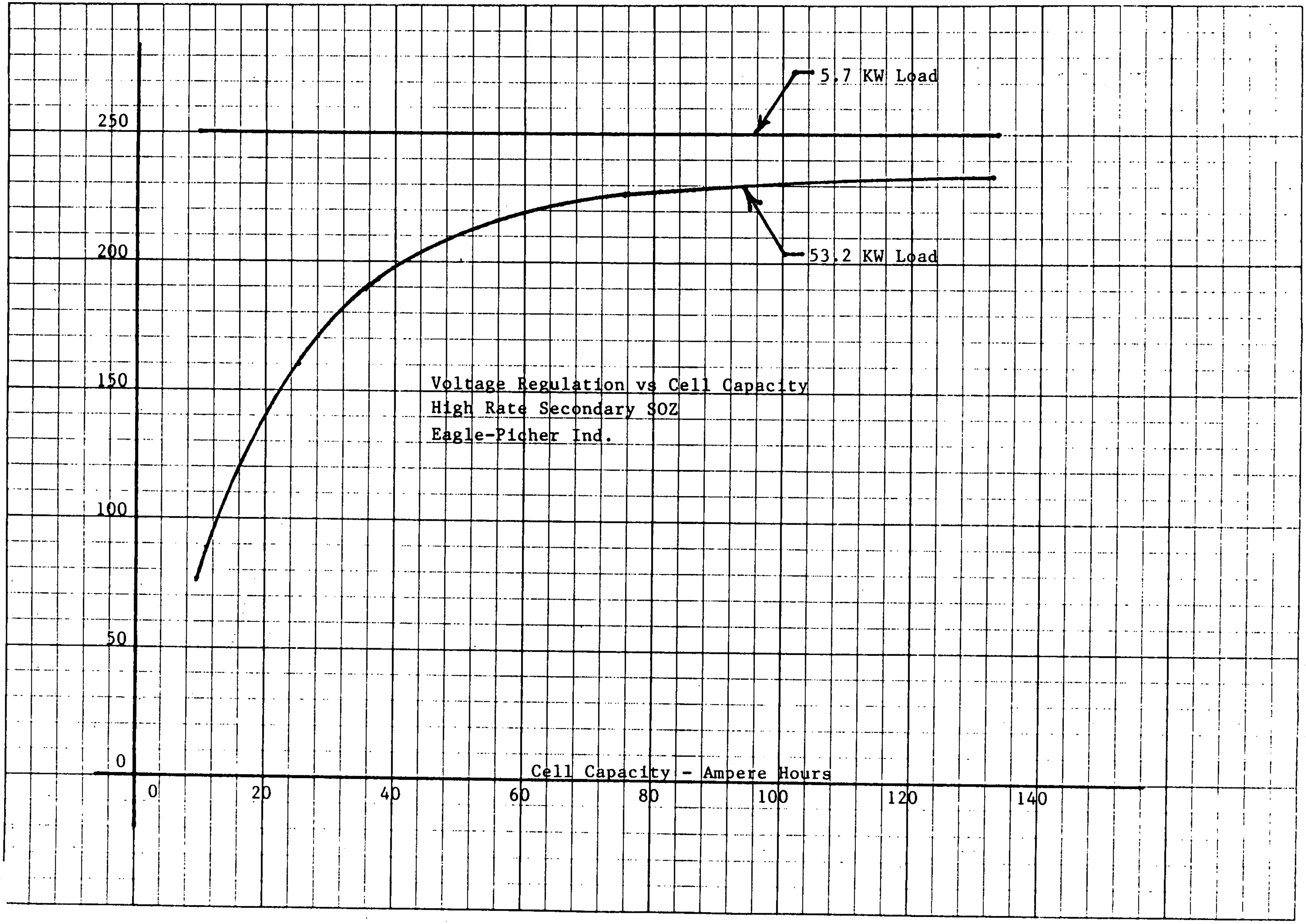
POWER SOURCE REQUIREMENTS

VOLTAGE 260 - 200 VDC
BASE ELECTRICAL LOAD: 5.7 KW FOR 570 Seconds (9.5 Minutes)
PULSE LOAD: (5) 0.5 Sec. pulses of 53.2 KW Spaced By 10 Sec. Minimum
60 Day Minimum Activated Life
Minimum Maintenance After Installation
Testable at All Points Before Launch
Low Weight and Volume
High Reliability
No Special Provisions for Shipping, Storage, or Testing
Proven Safety

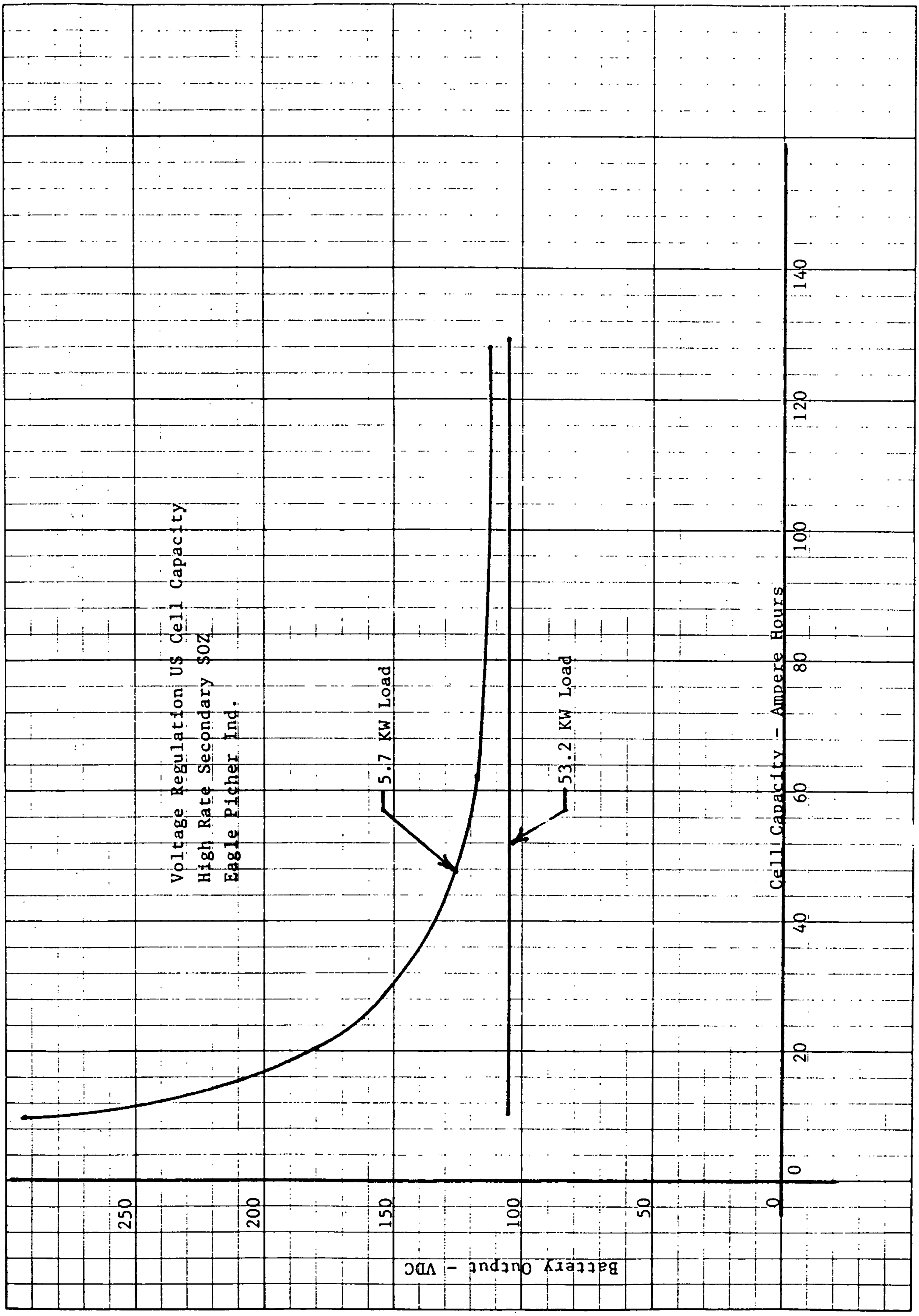


Specific Energy Density
vs Cell Size
Secondary SOZ
Eagle-Picher Ind.
Cell Capacity - Ampere Hours
0
20
40
60
80
100
120
140
Cell Output - Watts/lb.
0
100
200
300
400
500


Power Output US Load Rate
Secondary SOZ, 60AH
Eagle-Picher Ind.
Cell Output - Watts
800
600
400
200
0
.5 sec Pulse Load - C Rate
0
5
10
15
20
25
30
40



5.7 KW Load
53.2 KW Load
Voltage Regulation vs Cell Capacity
High Rate Secondary SOZ
Eagle-Picher Ind.
250
200
150
100
50
0
0
20
40
60
80
100
120
140
Cell Capacity - Ampere Hours


Voltage Regulation US Cell Capacity
High Rate Secondary SOZ
Eagle Picher Ind.
5.7 KW Load
53.2 KW Load
Cell Capacity - Ampere Hours
0
20
40
60
80
100
120
140
Battery Output - VDC
0
50
100
150
200
250

C-5

SECONDARY SILVER ZINC
DESIGN FOR MINIMUM WEIGHT

MAXIMUM ENERGY POINT ON CURVE APPROX. 20 C
SUPPLY 53.2 KW AT 200 VDC MIN
MAXIMUM VOLTAGE NOT REGULATED

318 CELLS 12.3 AH

WEIGHT - 170 LB.

VOLUME - 1.53 FT^3

AT 53.2 KW LOAD

210 VDC, 253 AMPS

AT 5.7 KW LOAD

478 VDC, 11.9 AMPS

SECONDARY SILVER ZINC DESIGN FOR VOLTAGE CONTROL

SUPPLY 53.2 KW AT 200 VDC MIN
SUPPLY 5.7 KW AT 260 VDC MAX

162 CELLS, 50 AH
WEIGHT - 358 LB.
VOLUME - 3.16 FT^3
AT 53.2 KW LOAD
210 VDC, 253 AMPS

AT 5.7 KW LOAD
250 VDC, 22.8 AMPS

RESERVE PRIMARY SILVER ZINC

SUPPLY 53.2 KW AT 200 VDC MIN

SUPPLY 5.7 KW AT 260 VDC MAX

158 CELLS, 5.7 AH

WEIGHT - 88 LB.

VOLUME - .85 FT^3

APPROXIMATE 15 MINUTE ACTIVATED LIFE

ACTIVATED LIFE UP TO 6 HR AVAILABLE WITH
20% WEIGHT AND VOLUME INCREASE

BIPOLAR SECONDARY SILVER ZINC

SUPPLY 53.2 KW AT 200 VDC MIN

SUPPLY 5.7 KW AT 260 VDC MAX

162 CELLS, 12.8 AH

WEIGHT 114 LB, VOLUME .70 FT^3

120 DAY ACTIVATED LIFE

WEIGHT REDUCTION
FOR
CONVENTIONAL SECONDARY SILVER - ZINC

1. ACTIVATED LIFE 30 TO 60 DAYS

2. RAISE OPERATING TEMPERATURE

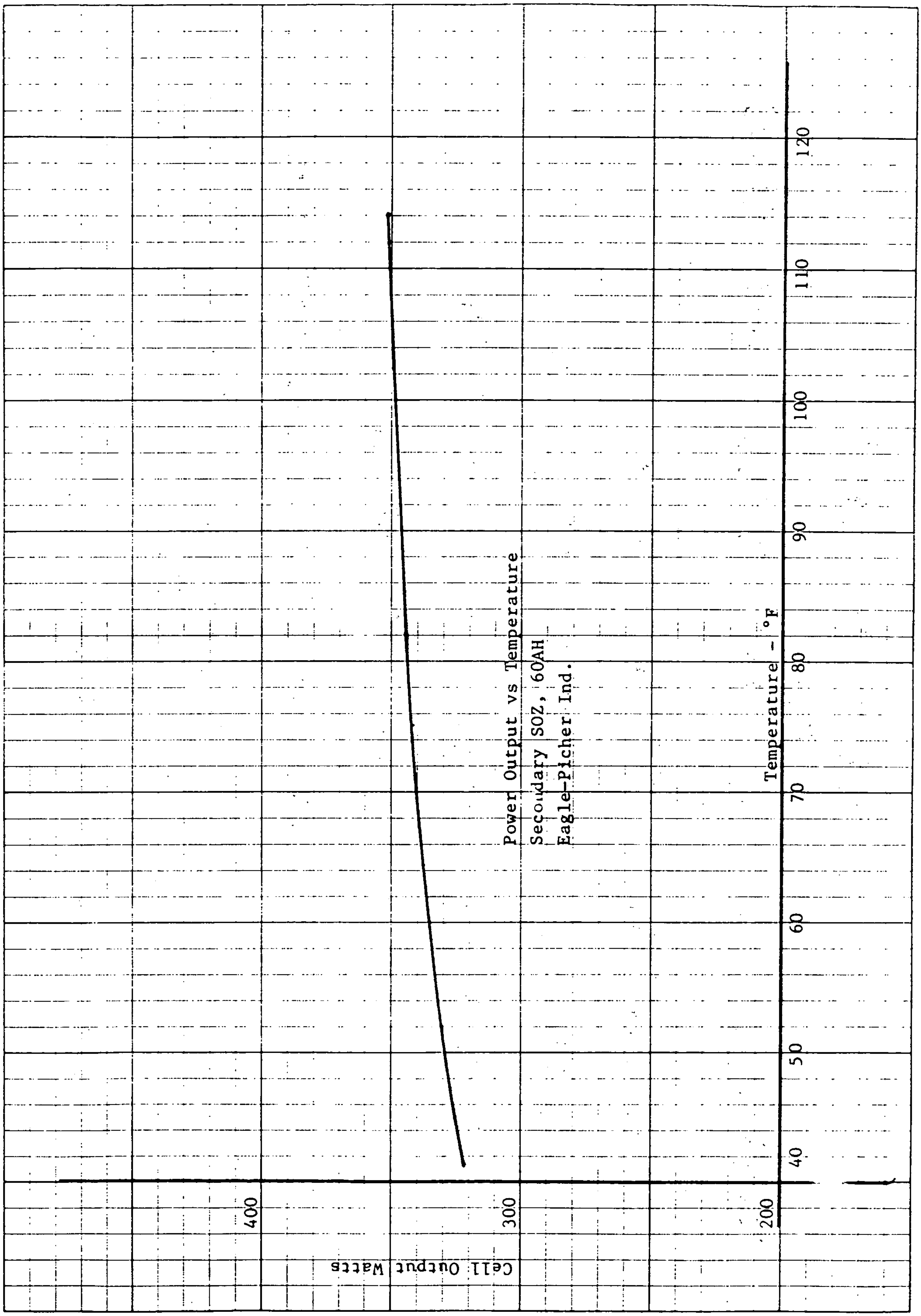
3. REFINE PHYSICAL CONFIGURATION

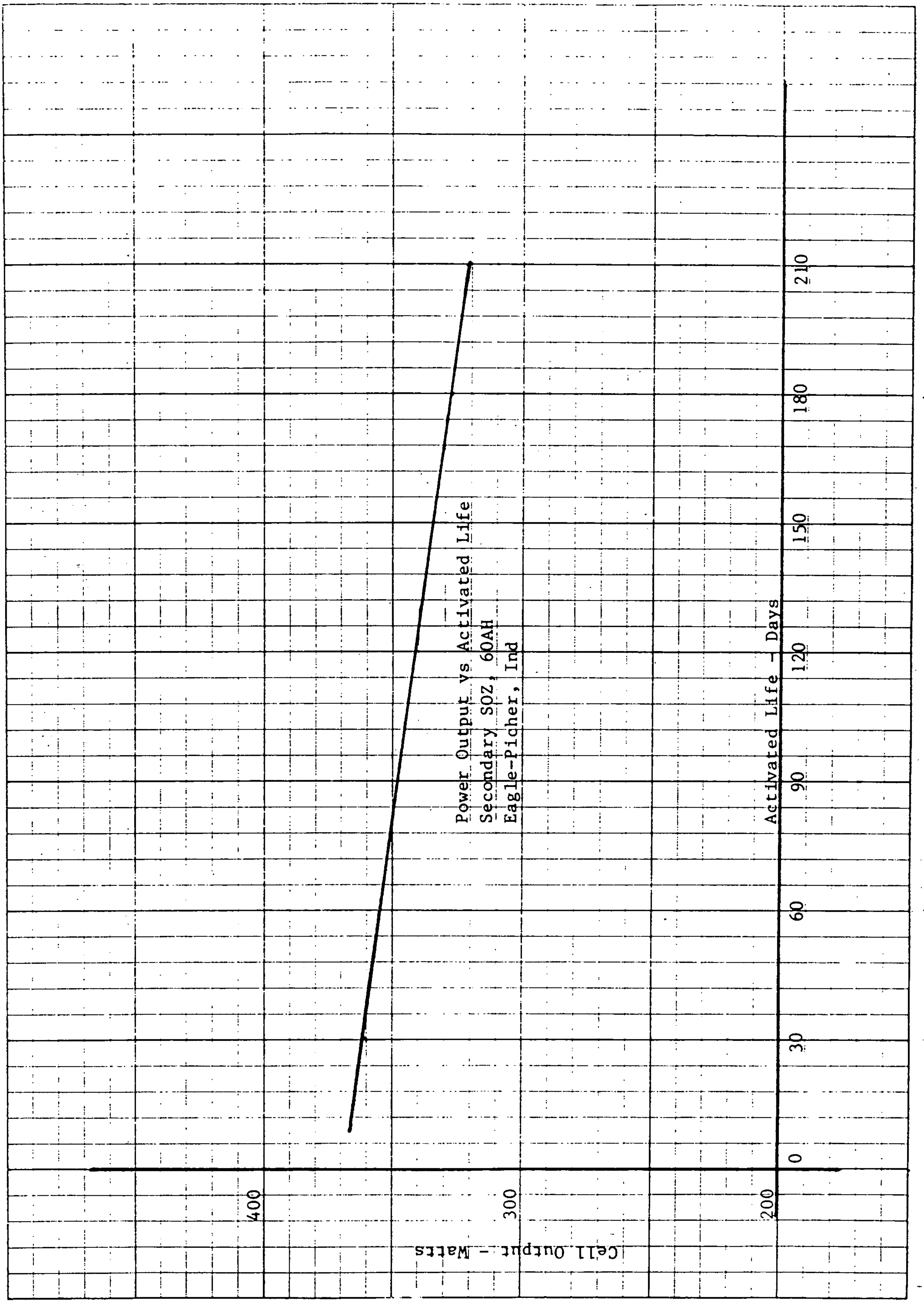
   A. MULTICELL MONOBLOCK

   B. INTERNAL INTERCELL CONNECTORS

   C. LIGHTWEIGHT CONTAINER MATERIAL - TITANIUM

4. INCREASE MAXIMUM VOLTAGE LIMIT


Power Output vs Temperature
Secondary SOZ, 60AH
Eagle-Picher Ind.
Temperature - °F
40
50
60
70
80
90
100
110
120
Cell Output Watts
200
300
400


Power Output vs Activated Life
Secondary SOZ, 60AH
Eagle-Picher, Ind
Activated Life - Days
0
30
60
90
120
150
180
210
Cell Output - Watts
200
300
400

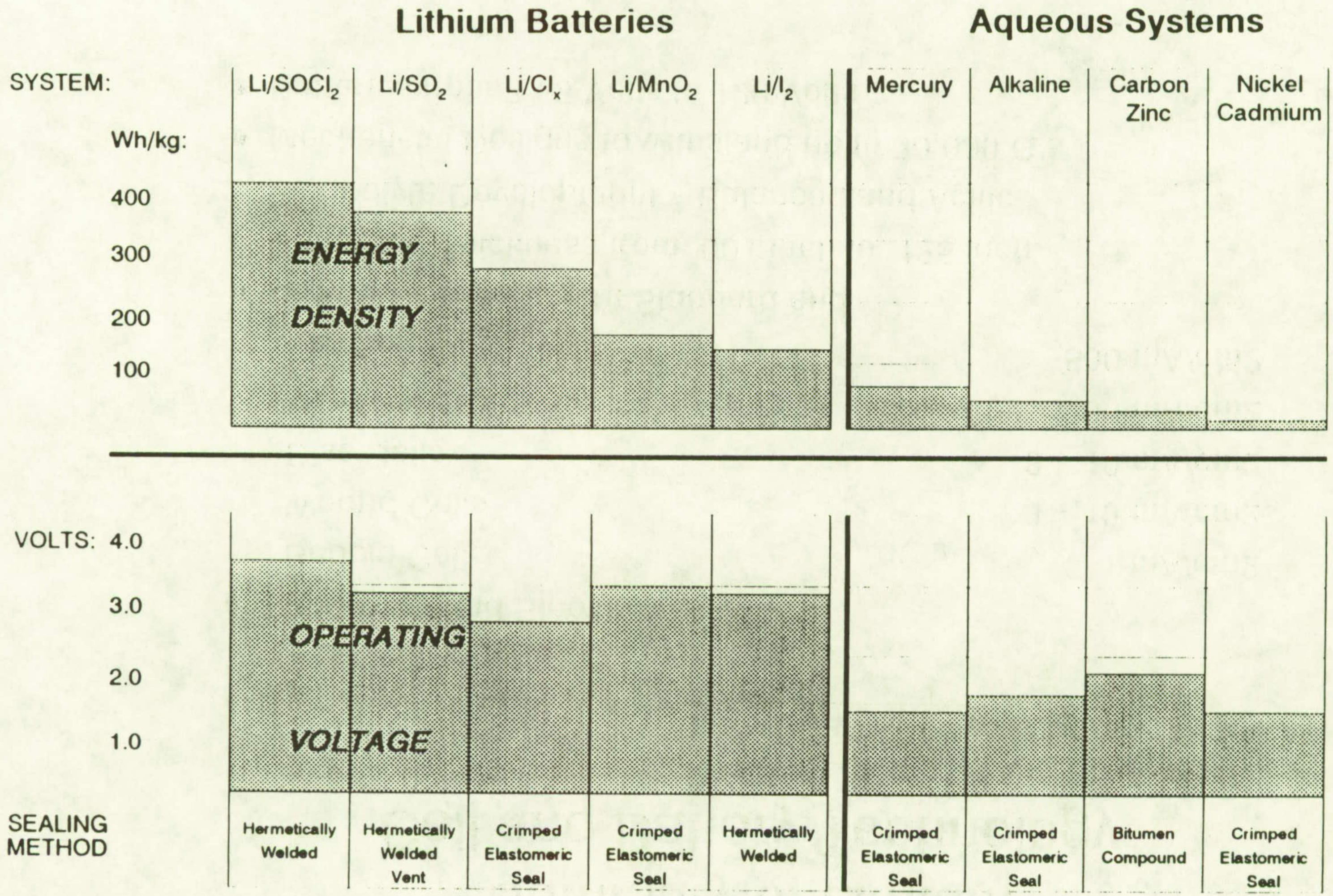
High Rate
Lithium Battery Technology

presented to the

Electrical Actuation Technology
Bridging Workshop

September 29 – October 1, 1992
Marshall Space Flight Center
Hunstville AL

Yardney Technical Products, Inc.
82 Mechanic Street   Pawcatuck CT 06379



Energy Density and Operating Voltage of Lithium Batteries and Most Common Commerical Batteries

GMT b:\slides\li−vs−aq

Yardney TECHNICAL PRODUCTS INC

Yardney

Summary of Lithium Cell and Battery Technology

Active and Reserve Batteries

- Monopolar and Bipolar

Bobbin Cells	1 mA/cm2
Wound Cells	3 - 10 mA/cm2
Disc Cells	3 - 10 mA/cm2
High Rate Batteries	20 - 100 mA/cm2
Special Applications (ALWT)	500 mA/cm2

- Cathode Development Standard and Catalyzed Thickness from .001 inch to .125 inch
- Electrolyte Development - Balanced and Acitic
- Mechancial Designs to withstand up to 30,000 G's
- Batteries from 3.65 Volts to 120 Volts

Yardney
TECHNICAL PRODUCTS INC

Capacity Losses on Storage at Room Temeprature after One Year

Type	*Approximate Loss*
Leclanche	12 – 15% per year
Alkali–Mn–O_2	3 –5% per year
Silveroxide–Zinc	5 – 10% per year
Mercury–Zinc	2 – 3% per year
Lithium	0.5 – 2% per year

Yardney

Advantages of Lithium Thionyl Choride

- –40° to +150° C. operating temperatures
- Long storage life
- High energy density
- Stable voltage
- Hermetically sealed
- Design versatility
- Reliable
- Excellent safety record
- Manufacturability

Vardney

Disadvantages of Lithium Thionyl Chloride

- Toxidity of Electrolyte
- Passivation of Anodes
- Hazardous above 180°C

Development of a High Power Bipolar Li/$SOCl_2$ Battery

Yardney Technical Products, Inc.
82 Mechanic Street
Pawcatuck CT 06379

Sponsors: Wright Patterson Air Force Base
September 1986 – July 1990

General Dynamics
May 1991 – October 1991

High Rate Primary Lithium Battery

Achievements Under WRDC Sponsorship

- Design and evolution of a sealed high rate bipolar $Li/SOCl_2$ battery
- 25kW pulsed discharge of an 80 cell module using 20ms pulses at 10% duty cycles
- Demonstration of practical pulse energy density of 1.9kW/lb.
- Demonstration of 100mA/cm^2 continuous and 400mA/cm^2 pulsed discharge
- Development of procedures for:
  - making .002–.010 inch carbon cathodes
  - heat sealing Tefzel insulators
  - filling electrolytes

Yardney Technical Products Inc

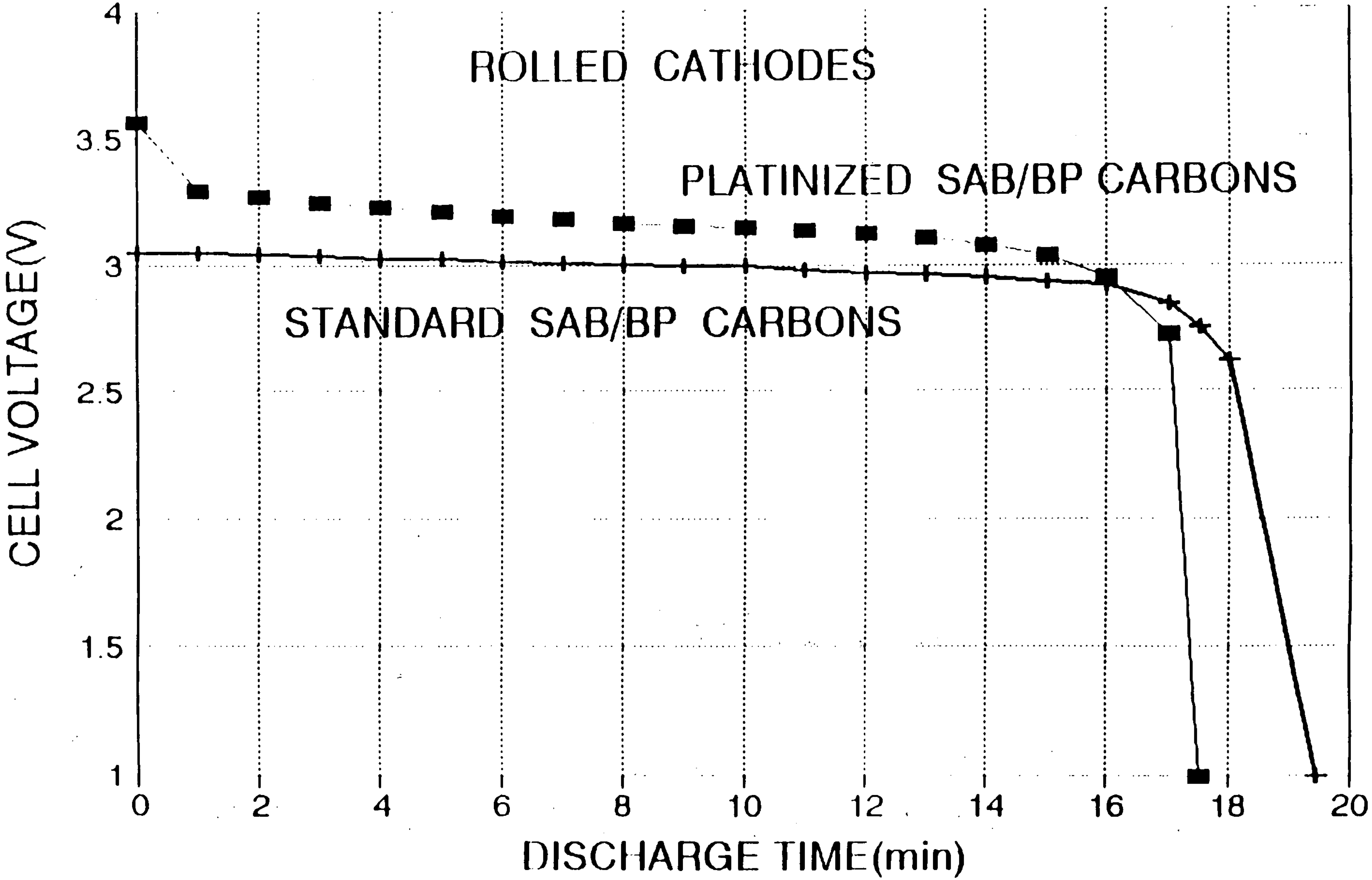
High Rate Pulse Discharge of 25kW 80 Cell Module

Test Sequence	Current (A)	Current Density (mA/cm^2)	Pulse Length (ms)	Pulse [1] Time (sec)	Average [2] Pulse Voltage (V)	Average Power Output (kW)	Max [3] Pulse Power (kW)	Specific[3] Power (kW/lb)
1	103	206	2	17	189	19.5	20.6	1.1
2	103	206	4	13	198	20.4	21.1	1.1
3	103	206	20	15	190	20.5	21.0	1.1
4	206	412	2	16	143	29.4	34.6	1.9
5	206	412	4	14	150	30.9	35.0	1.9
6	206	412	20	6 [4]	140	28.8	35.0	1.9

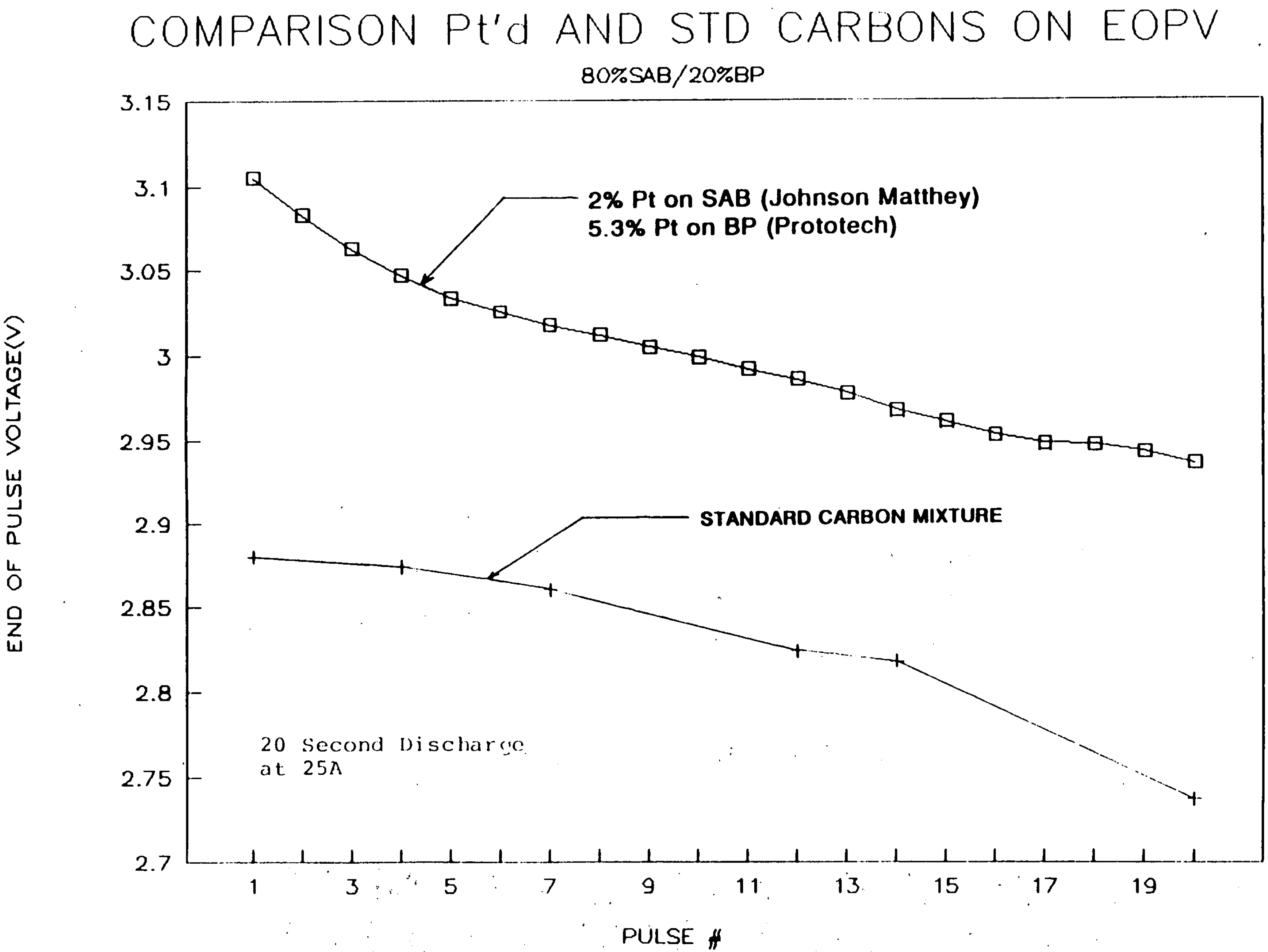
[1] 10% duty cycle
[2] Pulse voltage increased as battery warmed
[3] Based on highest pulse voltage. Battery weight is 18.6 lbs.
[4] Battery vented during previous pulse train. Lost current capability after six seconds. However, it delivered maximum power of 35kW.

Yardney TECHNICAL PRODUCTS INC

EFFECT OF PLATINIZED CARBON ON VOLTAGE CONTINUOUS DISCHARGE AT 25 mA/cm2

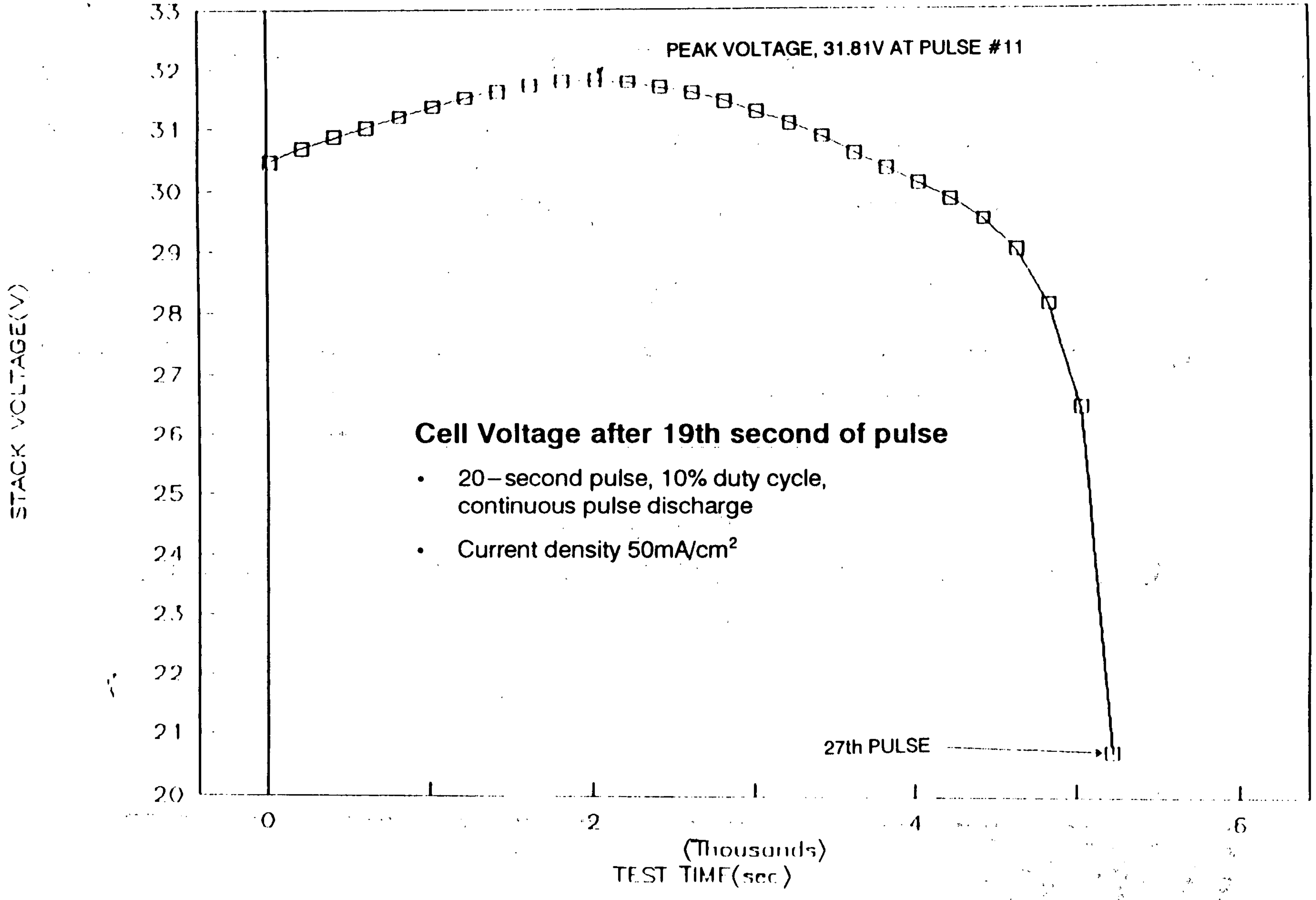


Vardney


COMPARISON Pt'd AND STD CARBONS ON EOPV
80%SAB/20%BP
END OF PULSE VOLTAGE(V)
3.15
3.1
3.05
3
2.95
2.9
2.85
2.8
2.75
2.7
2% Pt on SAB (Johnson Matthey)
5.3% Pt on BP (Prototech)
STANDARD CARBON MIXTURE
20 Second Discharge
at 25A
1
3
5
7
9
11
13
15
17
19
PULSE #

STACK VOLT. IN CONST. POWER PULSE TEST

10 CELL STACK,POWER 714 WATTS



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Yardney TECHNICAL PRODUCTS INC

Effect of Platinized Carbon on Cell Voltages vs Current Density in 1.6M $LiGaCl_4/SOCl_2$

Cathode Composition	Current Density in mA/cm²			Pulse #5 at End of Pulse Voltage (V)				
	25	50	75	100	150	200	250	300
Standard	3.27	3.04	2.85	2.70	2.44	2.21	1.99	1.75
BP W/5.3% Pt	3.26	3.07	2.92	2.78	2.55	2.40	2.26	2.11
SAB w/8.5% Pt	3.36	3.25	3.15	3.06	2.91	2.76	2.63	2.48
Both carbons platinized	3.32	3.23	3.15	3.08	2.94	2.81	2.69	2.57

Table 1
Full-Size [1] Single Cell Test Summary

Yardney TECHNICAL PRODUCTS INC

TEST	ROLLED CATHODE Composition[2]	ROLLED CATHODE Avg. Thk. (mil) [3]	H&V Separator Thk. (mil) [3]	Thionyl chloride Electrolyte	Fifth pulse [4] Voltage @ 250mA/cm²(V)	Continuous Discharge [5] Time (min.)	Total Capacity (Ah)	Cathode Capacity (Ah/cc) [6]
1	Standard	8.4	6.8	1.6M LiGaCl4	1.99	19.45	4.52	0.46
2	Standard	7.6	6.8	1.57M LiAlCl4	1.93	11.00	2.77	0.298
3	BP w/5.4% Pt	8.2	6.4	1.6M LiGaCl4	2.26	19.91	4.62	0.458
4	SAB w/8.5% Pt	8.3	5.3	1.6M LiGaCl4	2.63	14.33[7]	3.44	0.343
5	Both carbons platinized	7.2	4.9	1.6M LiGaCl4	2.69	17.50	4.12	0.461

[1] Ten-inch diameter electrode components

[2] 80% SAB / 20% BP

[3] Inital thickness; test cell thickness was adjusted so that the combined cathode/separator final thickness was 90% of their combined initial thicknesses.

[4] The 53.2kW power output requires a load current density of $250mA/cm^2$

[5] Continuous discharge 24.5 mA/cm^2 follows the last series of five half-second pulses at ten second intervals (5% of dury cycle). Pulse series were run at current densities of 25,50,75,100,150,200,250 and $300mA/cm^2$. These current densities are basedon full-size cathodes with no channels.

[6] Cathode volume corrected for channels

[7] Cell leaked electrolyte through plug in anode steel endplate.

Yardney TECHNICAL PRODUCTS INC

VOLTAGE DELAY:	• Low temperature storage • Pre–discharge conditioning MESP Centaur • 1.6M $LiGaCl_4$ / platinized cathodes • Additives: PVC, SO_2, $GaCl_3 \bullet SO_2$, $Li_2O \bullet GaCl_3$
RECHARGEABLE:	No problem with millisecond charge pulses
HANDLING:	• Designed for shock and vibration • Insulate terminals • Low temperature storage
SAFETY:	• Battery will not overheat within load range
BATTERY CHECK PRIOR TO LAUNCH:	• OCV • Leaks/corrosion • Pre–discharge conditioning • Verify rate by pulse load testing

EMA Performance Requirements

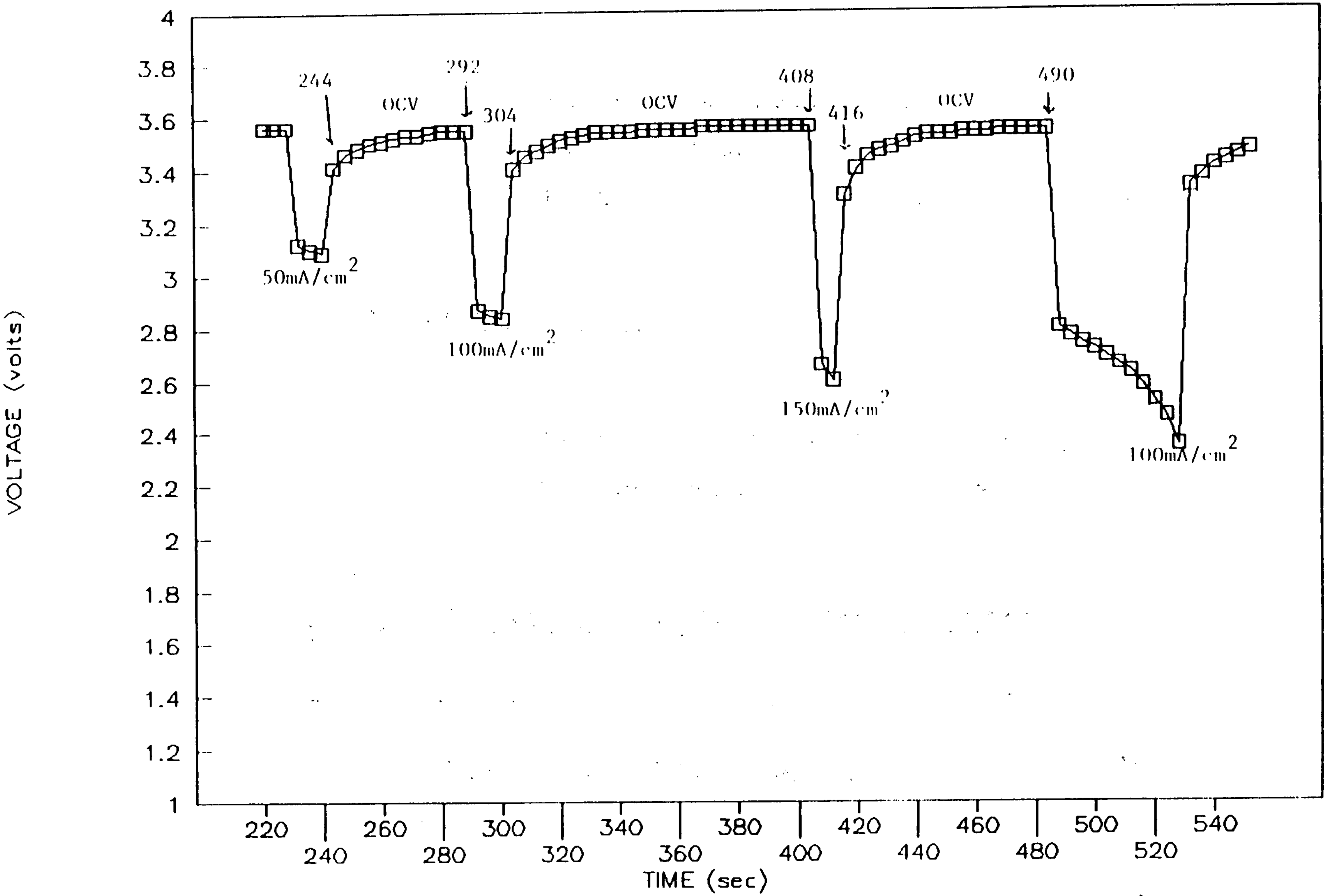
- 200 Volts
- 53 kW Pulses (Five pulses, 0.5 seconds each)
- 12.5 Amp background current for 600 seconds

Design Approach:

- Bipolar Li/SOCl Battery
- Two parallel battery stacks, with 80 cells in each stack
- 125 Ampere (maximum current)
- 250 mA/cm^2 (maximum current density)

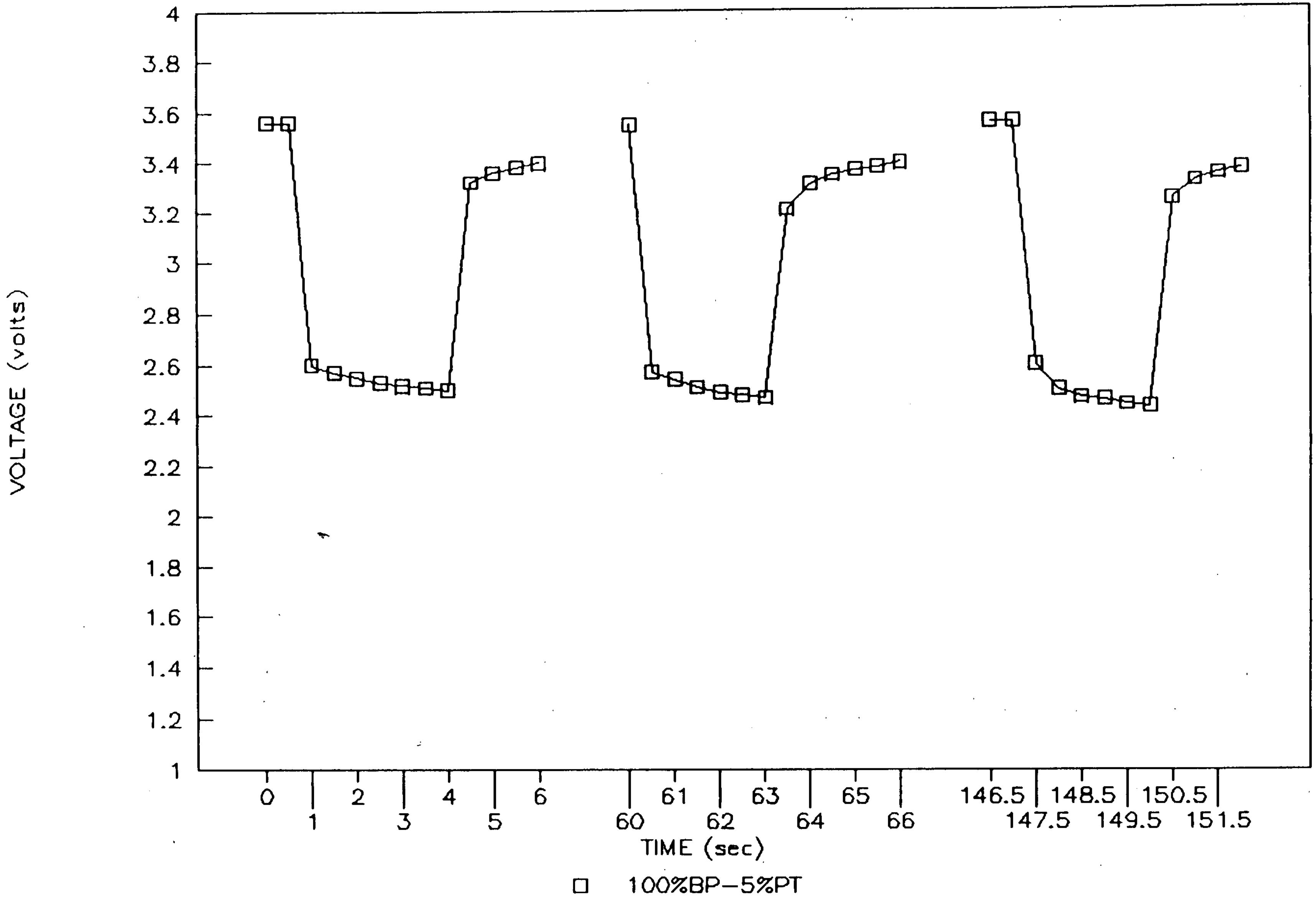
HIGH RATE $SOCl_2$ CELL

100%BP–5%PT



HIGH RATE SOCl² CELL

DISCHARGED AT 260mA/cm²



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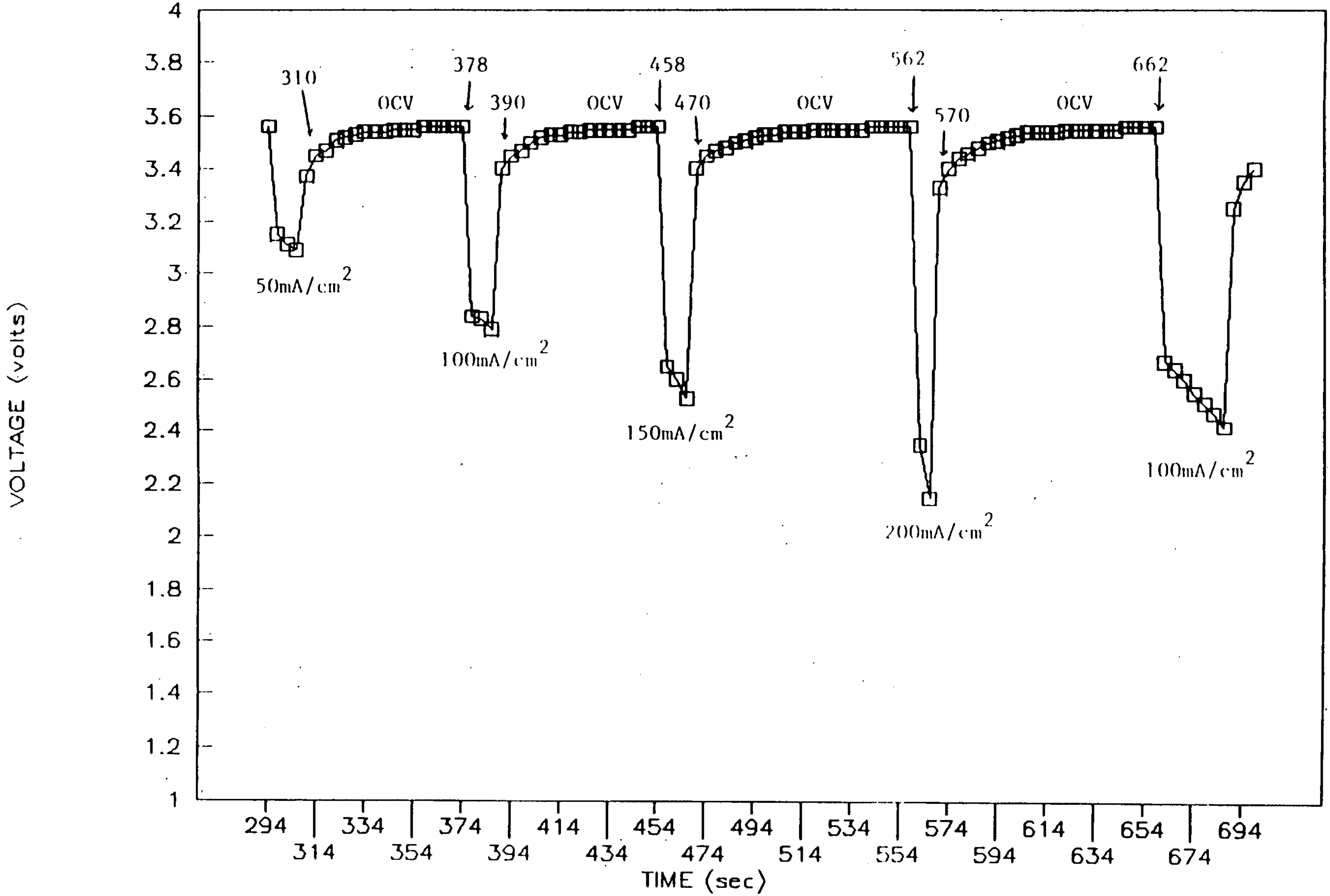
HIGH RATE $SOCl_2$ CELL

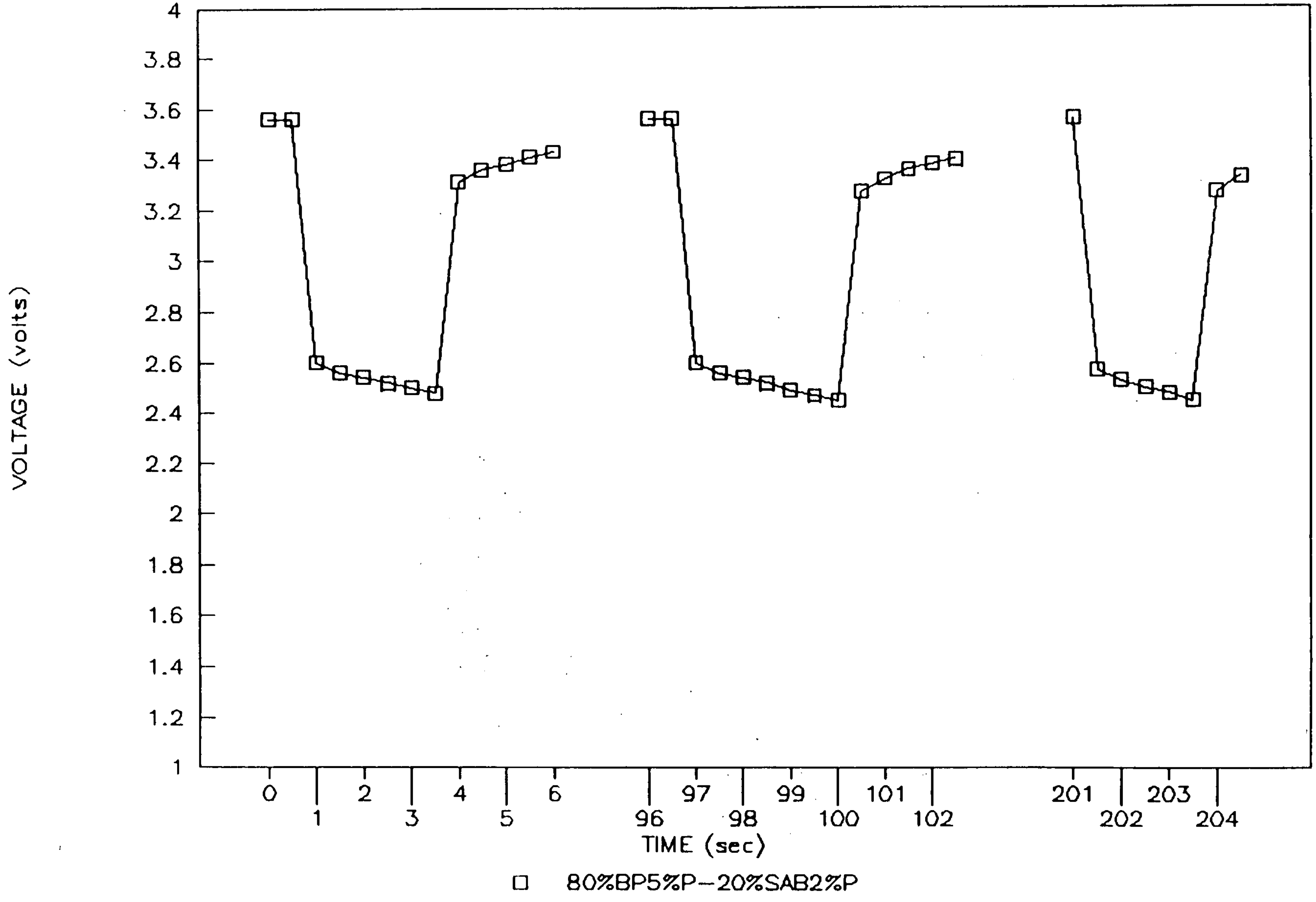
80%BP–5%PT 20%SAB–2%PT



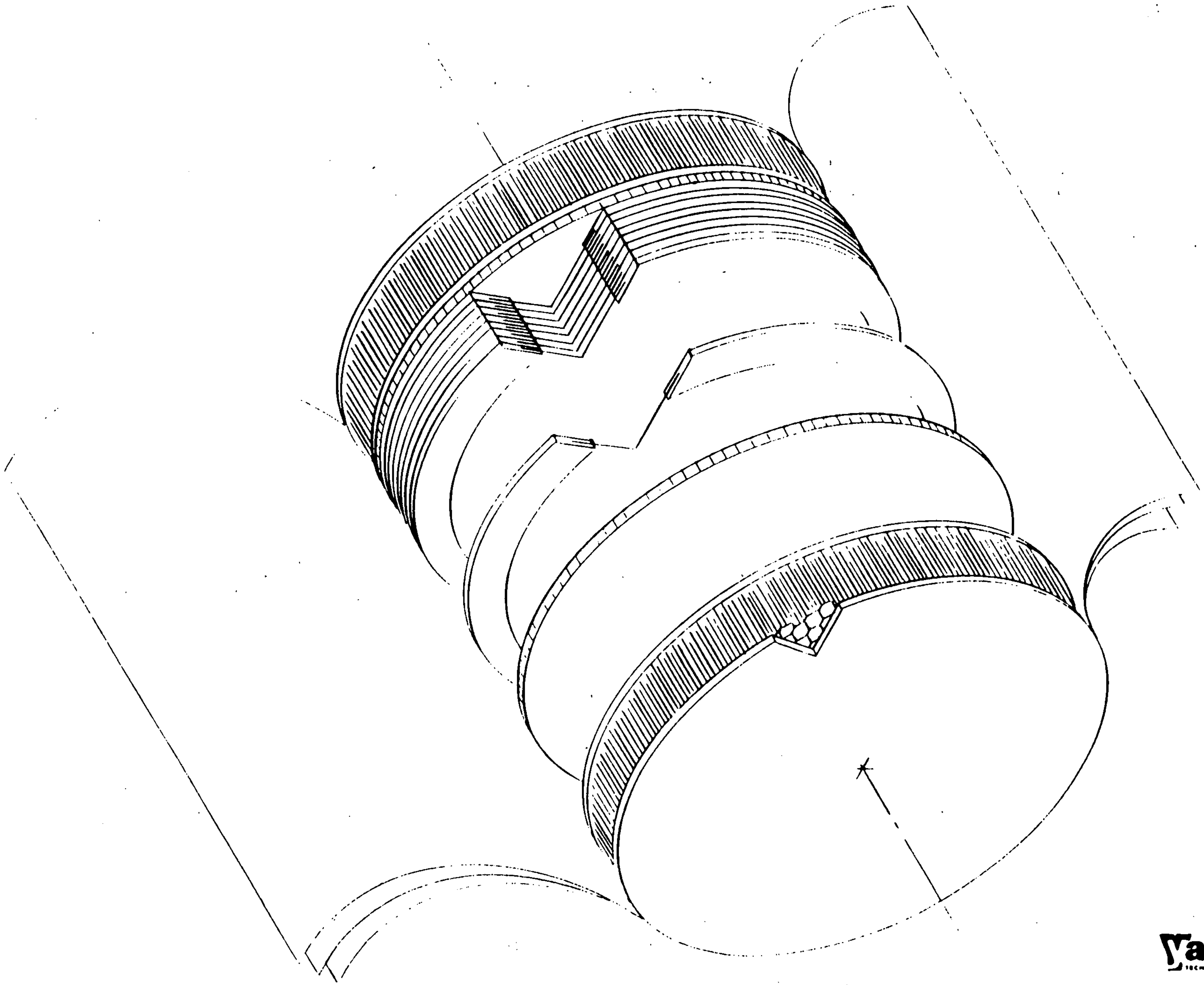
Yardney TECHNICAL PRODUCTS INC

HIGH RATE SOCl² CELL

DISCHARGED AT 260mA/cm²



Yardney



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Multi Cell Bipolar Battery

Figure 5A: Tefzel/nickel sandwich prior to compression molding

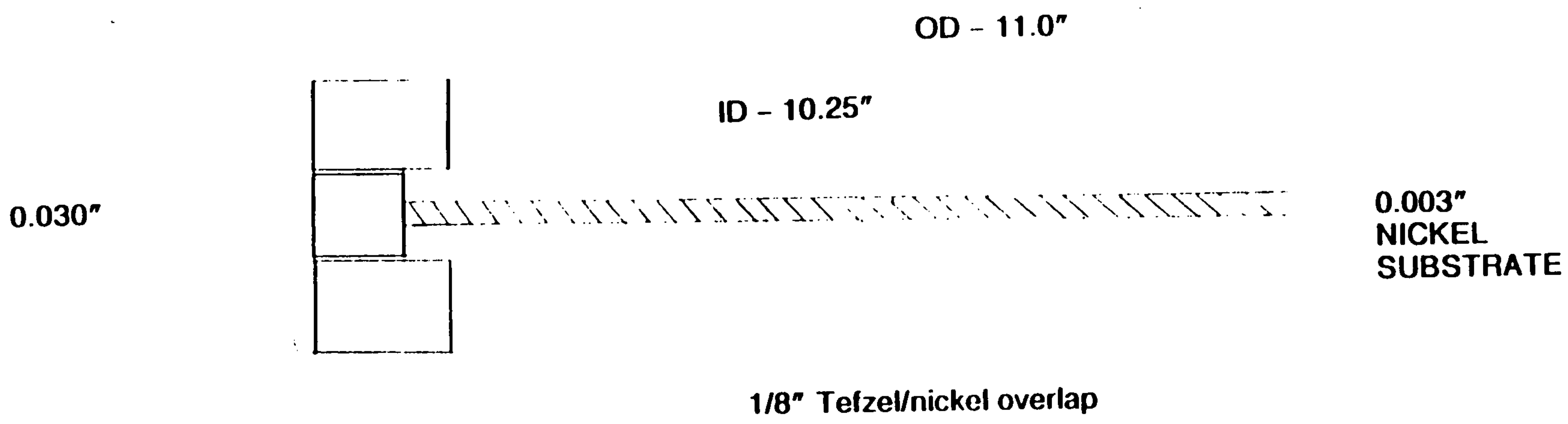
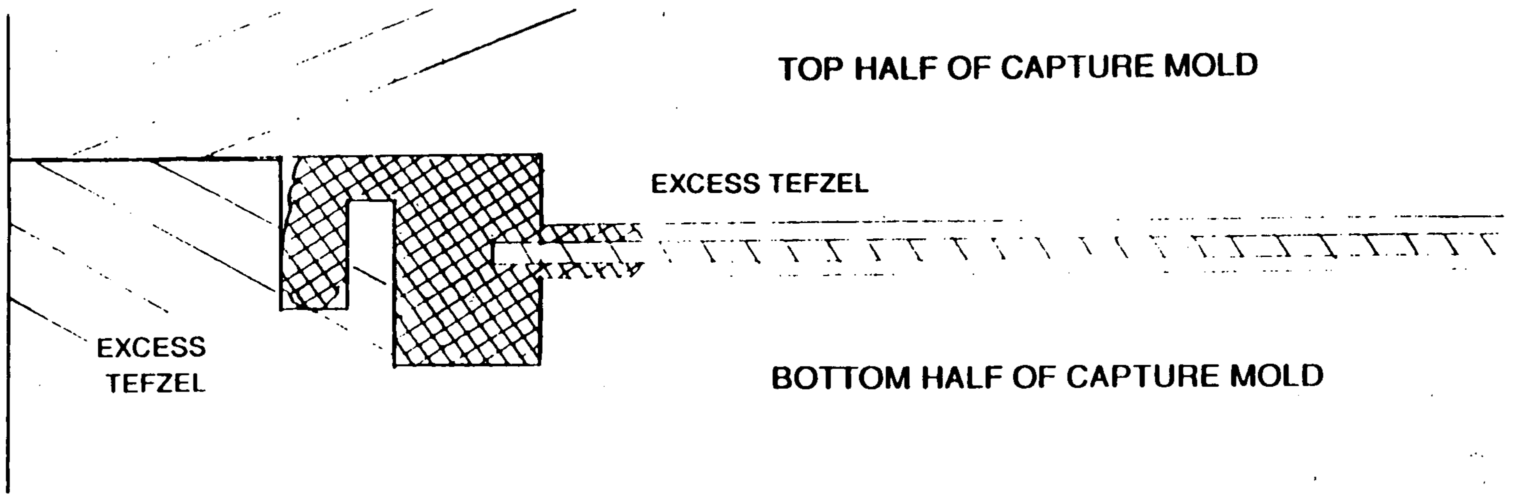


Figure 5B: Tefzel/nickel substrate configuration after compression molding



Average insulation ring height is 0.0224" for 1 mil substrate mold

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Yardney TECHNICAL PRODUCTS INC

EMA Power Module Design Concept

ELECTRICAL

- Voltage Range – 200 to 260 volts
- Base Power – 5.7kW for 570 seconds
- Pulse Power – 53.2kW, 5 pulses (each 0.5 sec. with 10 sec. separation

MECHANICAL

- 2 Parallel Submodules – 80 cells each
- Module Diameter – 11.5 inches
- Module Height – 7.5 inches
- Module Weight – < 30 lbs.

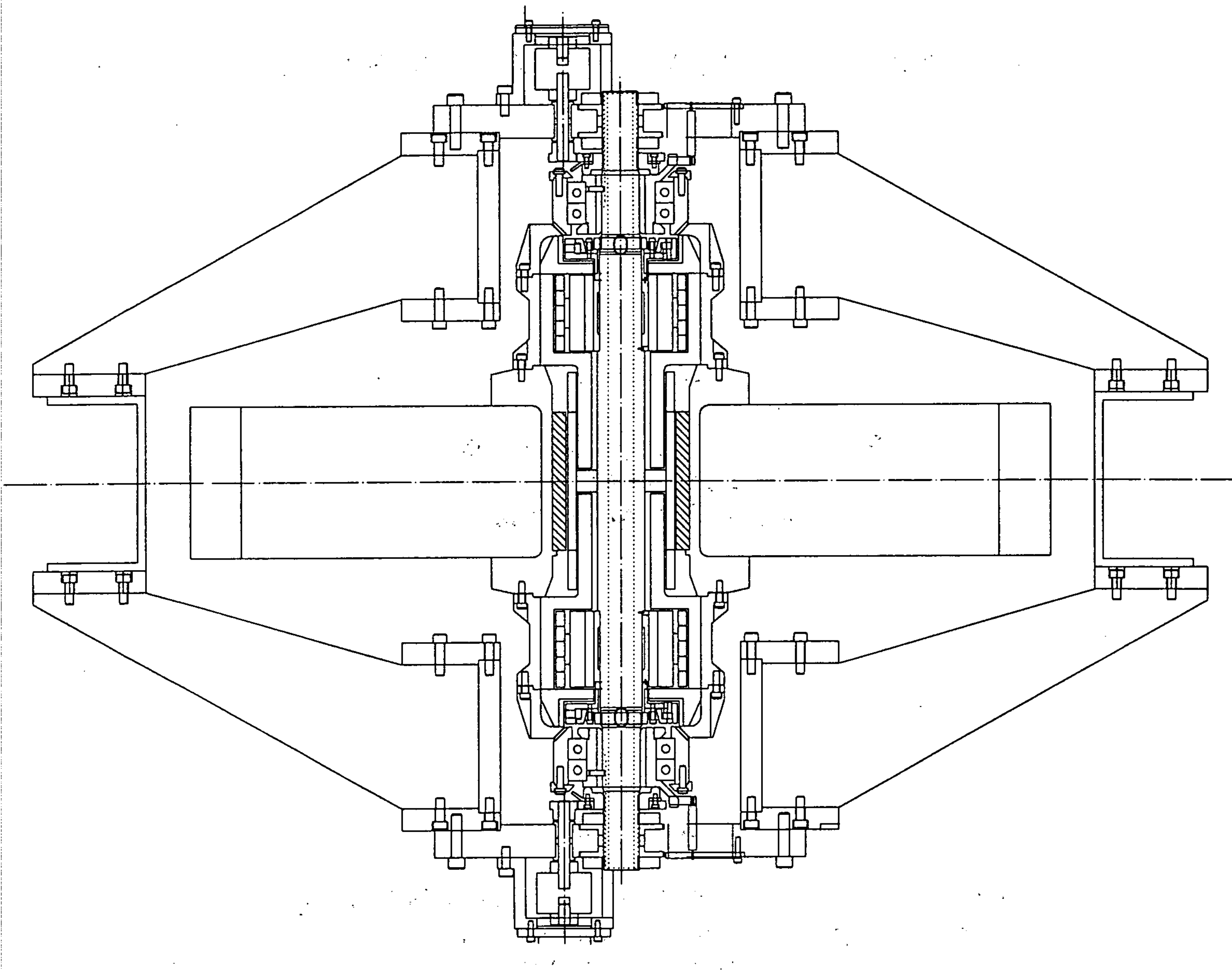
ELECTROMECHANICAL ACTUATION TECHNOLOGIES

Presented by:

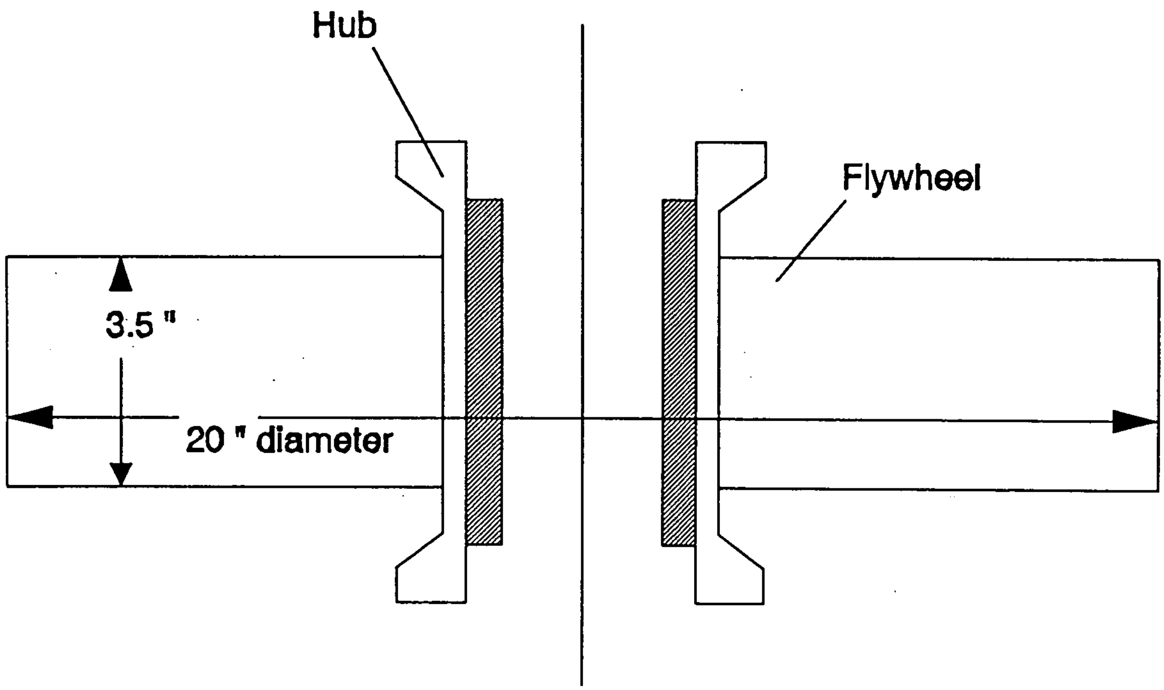
SatCon Technology Corporation
12 Emily Street
Cambridge, MA 02139

Presented to:

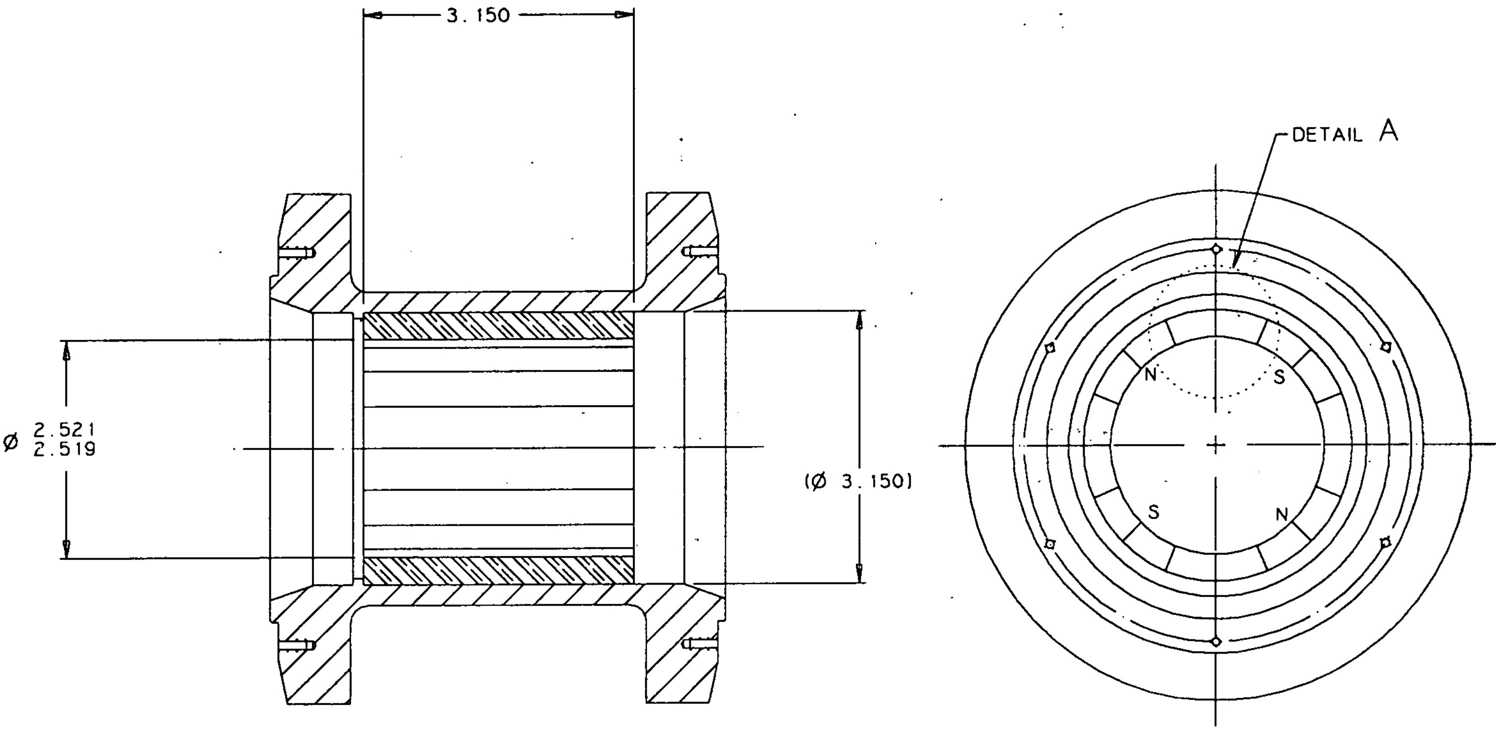
Electrical Actuation Technology Bridging Workshop
September 29 - October 1, 1992
Huntsville, Alabama



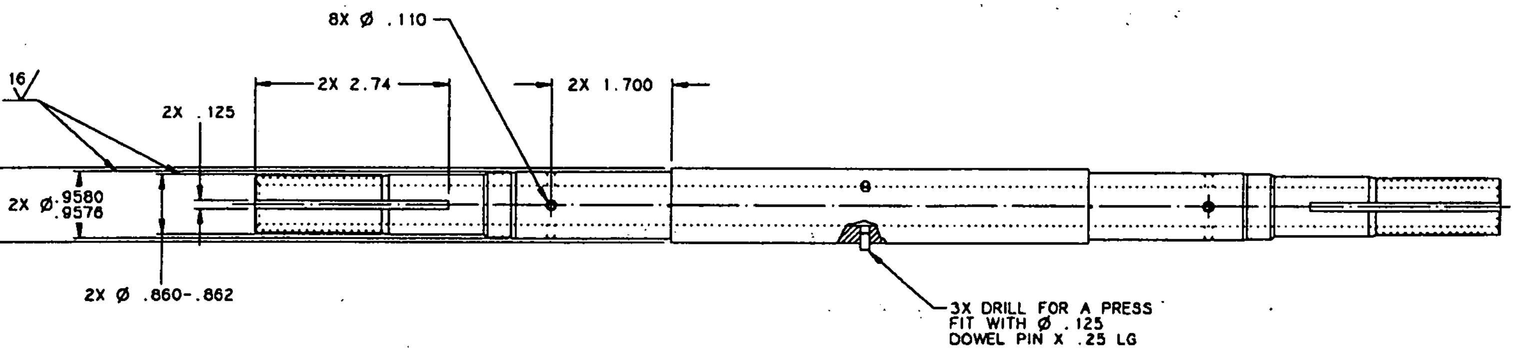
FLYWHEEL ENERGY STORAGE SYSTEM
ASSEMBLED SYSTEM



FLYWHEEL ON HUB



INTEGRATED FLYWHEEL HUB MOTOR/GENERATOR ROTOR



CENTRAL SHAFT FOR INTEGRATING MOTOR/GENERATOR STATOR, MAGNETIC BEARINGS AND TOUCH-DOWN CERAMIC BEARING

Weight measurements of the IPACS assembly (wheel energy 7.2 MJ)

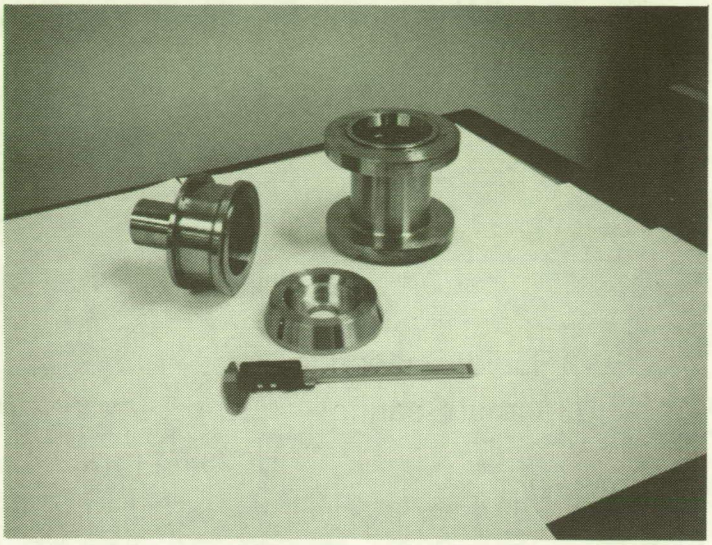
Weights as measured and best estimates (*)

Mechanical System

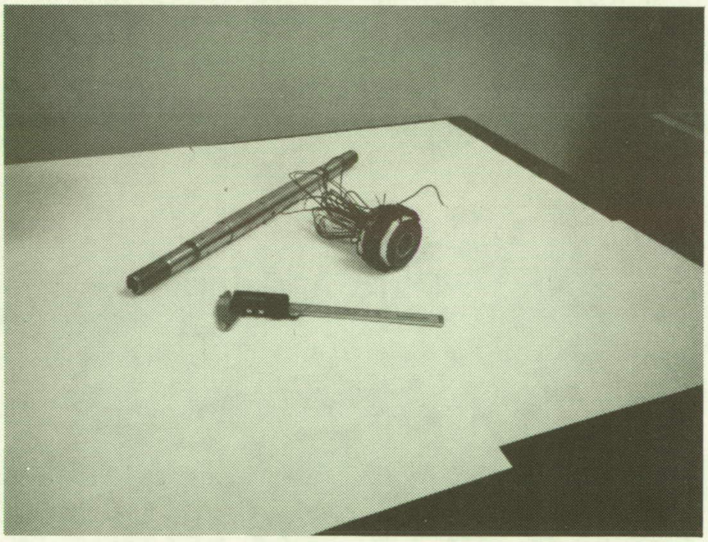
Flywheel (Fiber structure only)	25.0 kg
Motor/Generator Hub	5.0 kg
Central Shaft + Bearing Assembly + Motor/Generator Backiron	13.6 kg
Frame	12.0 kg
	55.6 kg
Containment (*) Estimate of light, thin shell containment	10.0 kg
	65.6 kg

Electronics System

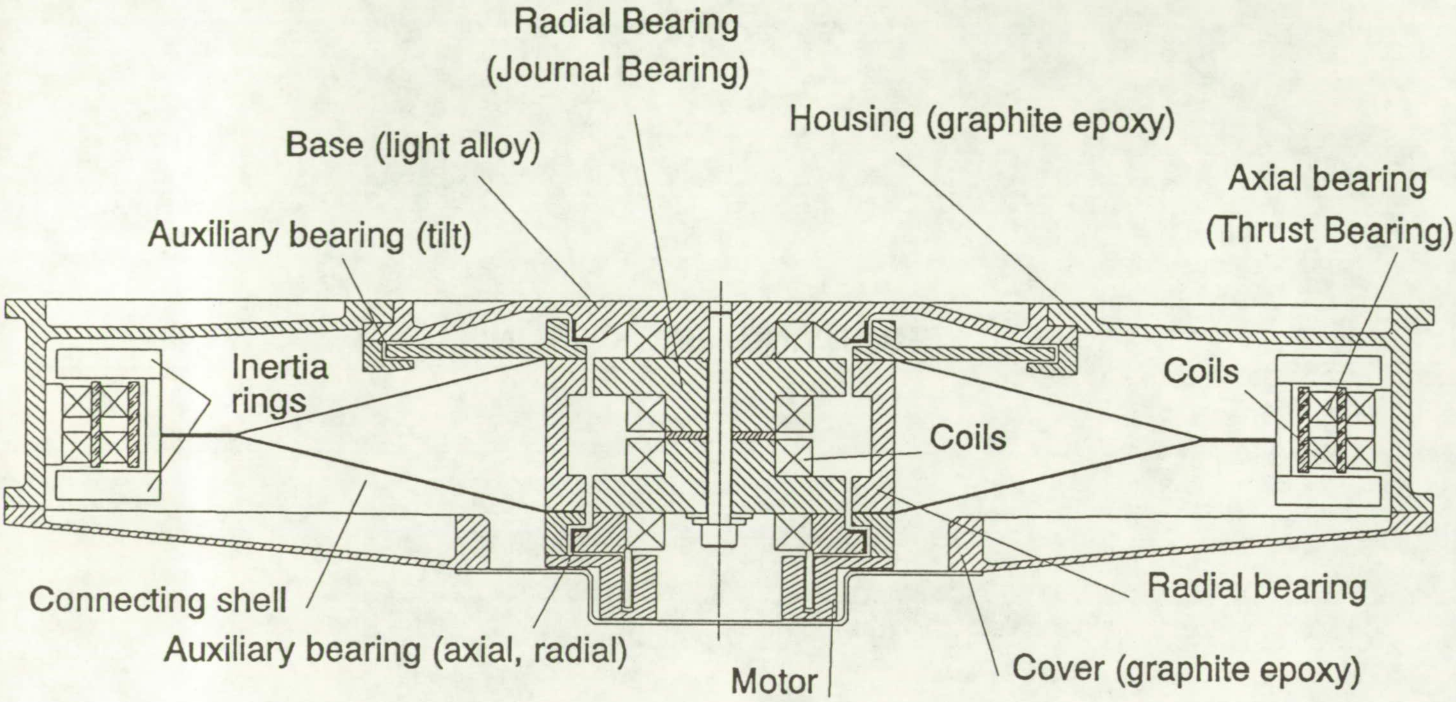
Inverter for Motor/Generator (3kW)	5.0 kg
Magnet Bearing Switching Amplifiers (*) + Sensor Electronics (*)	10.0 kg
	15.0 kg
Analog Amplifiers currently in use (extreme conservative choice to cover all possible variations of power and frequency response requirements)	60.0 kg



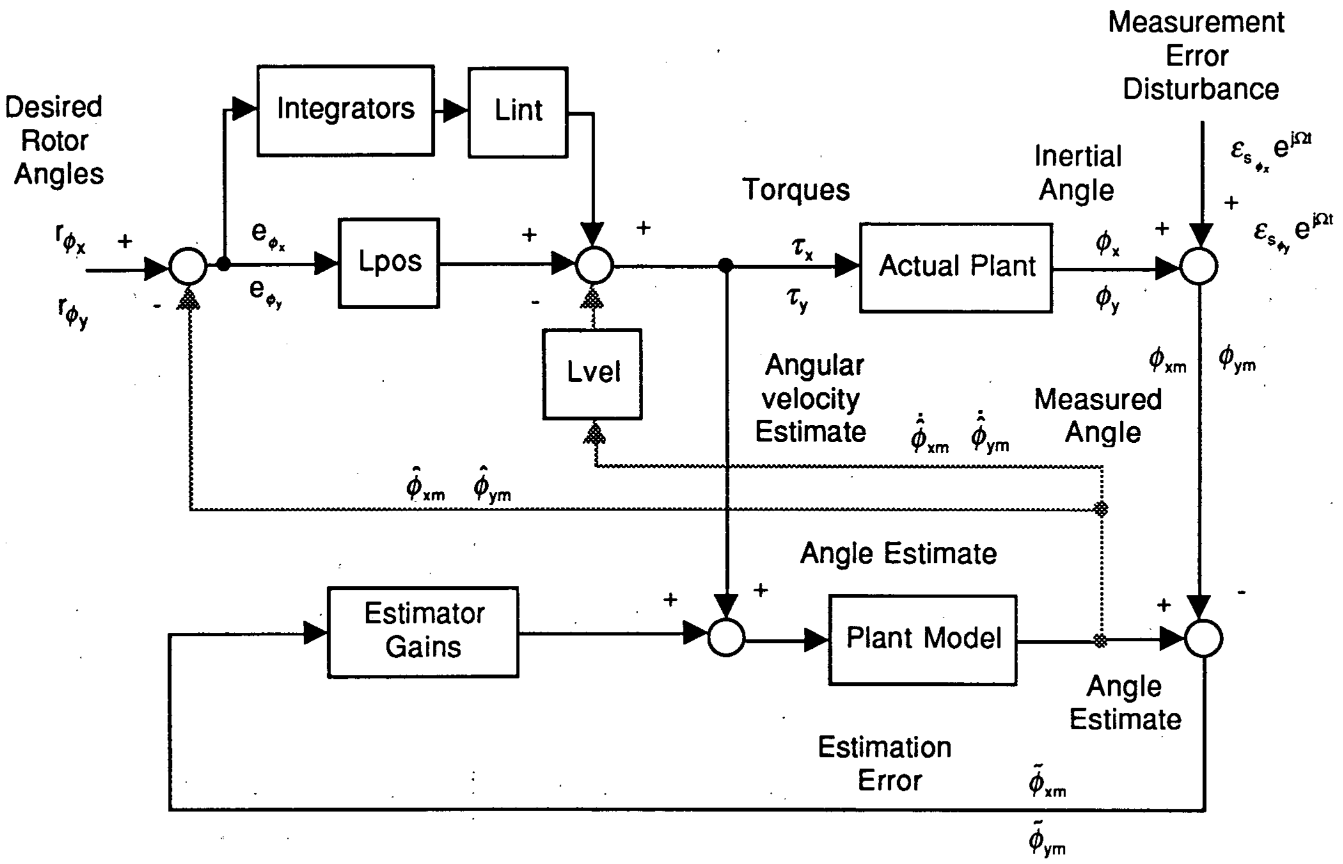
HUB AND BACK IRON



ONE MAGNETIC BEARING + MOUNTING SHAFT



MAGNETICALLY SUSPENDED MOMENTUM WHEEL COMPONENT LAYOUT



DISTURBANCE ACCOMMODATING CONTROLLER BLOCK DIAGRAM

	TELDIX DR-68 Momentum Wheel	SatCon Low Vibration Momentum Wheel
Total Mass	8 Kg	8.3 Kg
Dimensions	350 mm Diameter 120 mm Height	384 mm Diameter 88 mm Height
Steady State Power	< 26.5 Watts	< 10 Watts in 1g < 5 Watts in 0g
Maximum Wheel Precession Rate	--	0.03 rad/sec in 1g 0.08 rad/sec in 0g (min. required 7.6×10^{-3})
Torque Vibration at GOES Spacecraft Mass Center	Forces at 6000 rpm with 0.75 gm cm residual static imbalance F = 4.7 N Measured at 6000 rpm Tx = 7.46 Nm Ty = 6.83 Nm Tz = 7.46 Nm	Forces at 6600 rpm assuming 0.75 gm cm static imbalance F = 0.27 N Simulated including measurement error Tx = Ty = Tz < 0.7 Nm

MOMENTUM WHEEL PARAMETERS

INDUCTION-MACHINE/FLYWHEEL ENERGY STORAGE SYSTEM

Objective: Design flywheel energy storage system based on induction machine to interface with 20 kHz pulse-density modulation (PDM) converter.

Specifications:

Usable energy	250 kJ
Peak output power	36 kW
Output power risetime	1 kW/mSec
Average output power	4 kW

Goals:

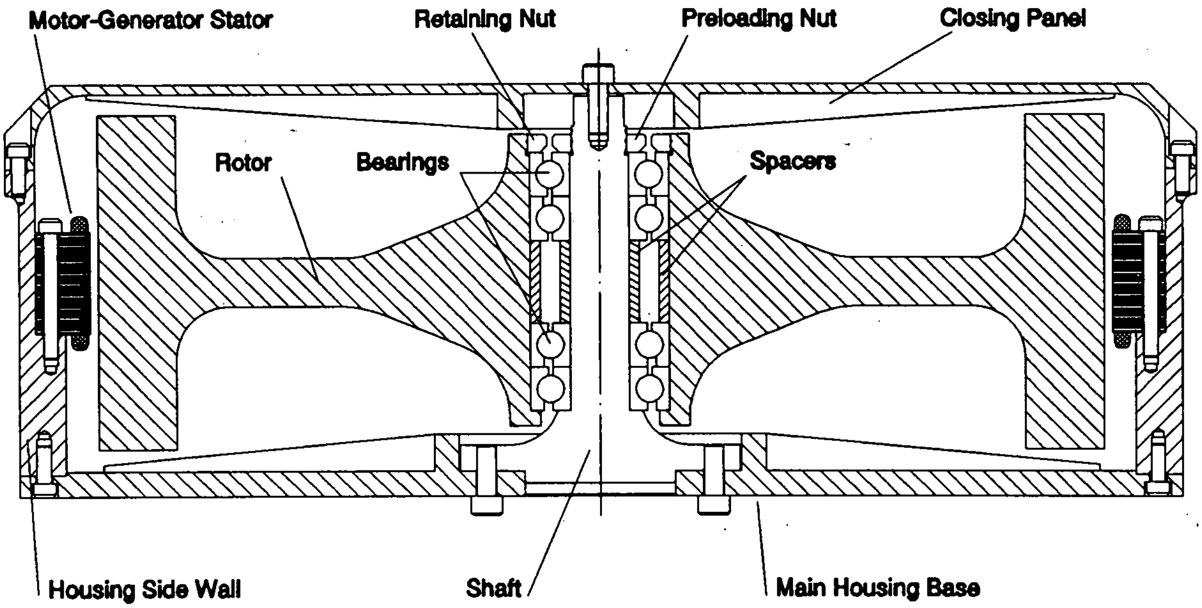
Efficiency (round trip)	80%
Power density	2 kW/kg
Energy density	100 kJ/kg

Absorb energy at 40 kHz

Low machine loss with PDM waveform

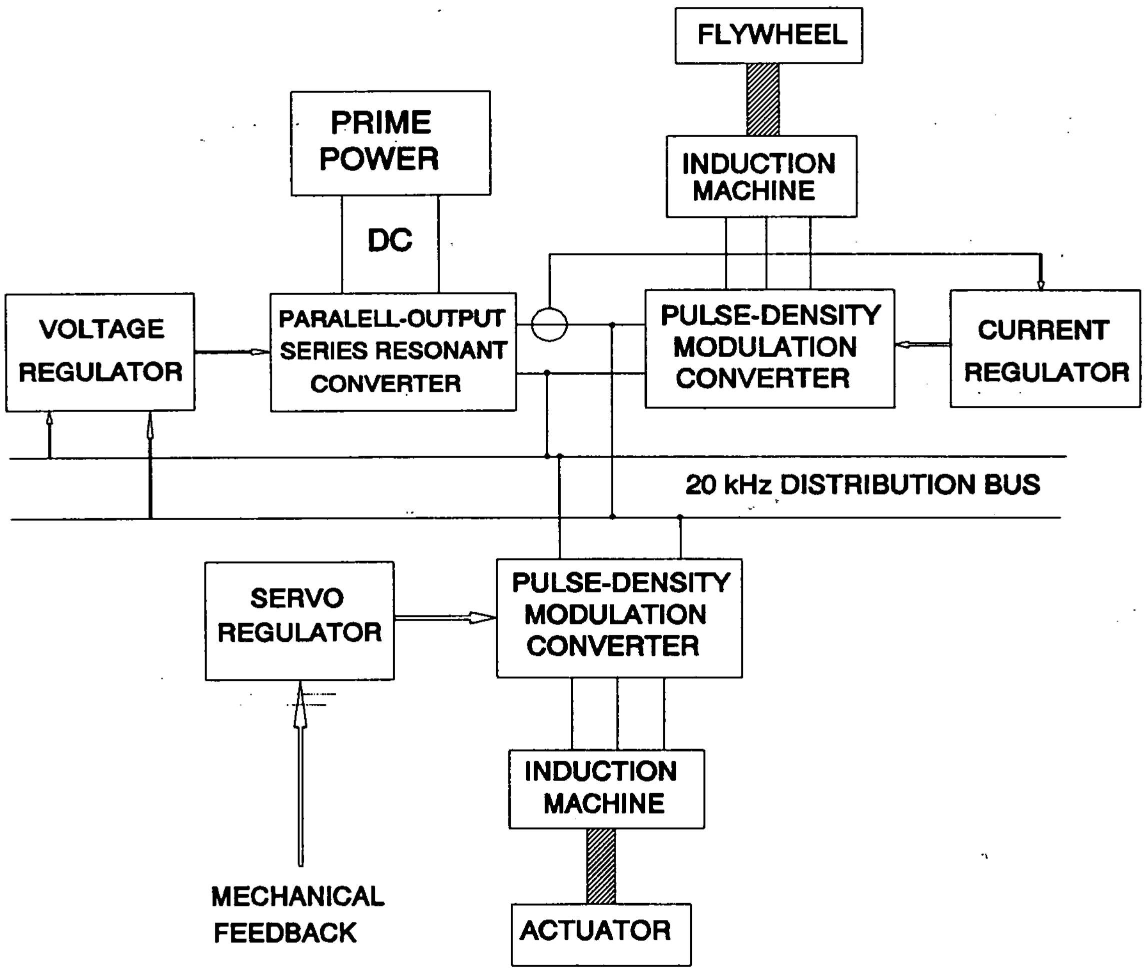
High-efficiency machine-control algorithm

FLYWHEEL ASSEMBLY LAYOUT



SIZE: 12 inch dia. X 4 inch ht.

BASELINE SYSTEM WITH DC PRIME SOURCE



SUMMARY

SPEED	24,000 rpm
MASS	22 kg
VOLUME	450 cubic inches
ROUND-TRIP EFFICIENCY	85%
VACUUM	16 torr
TEMPERATURE RISE	15 deg. K

Power Source Presentation

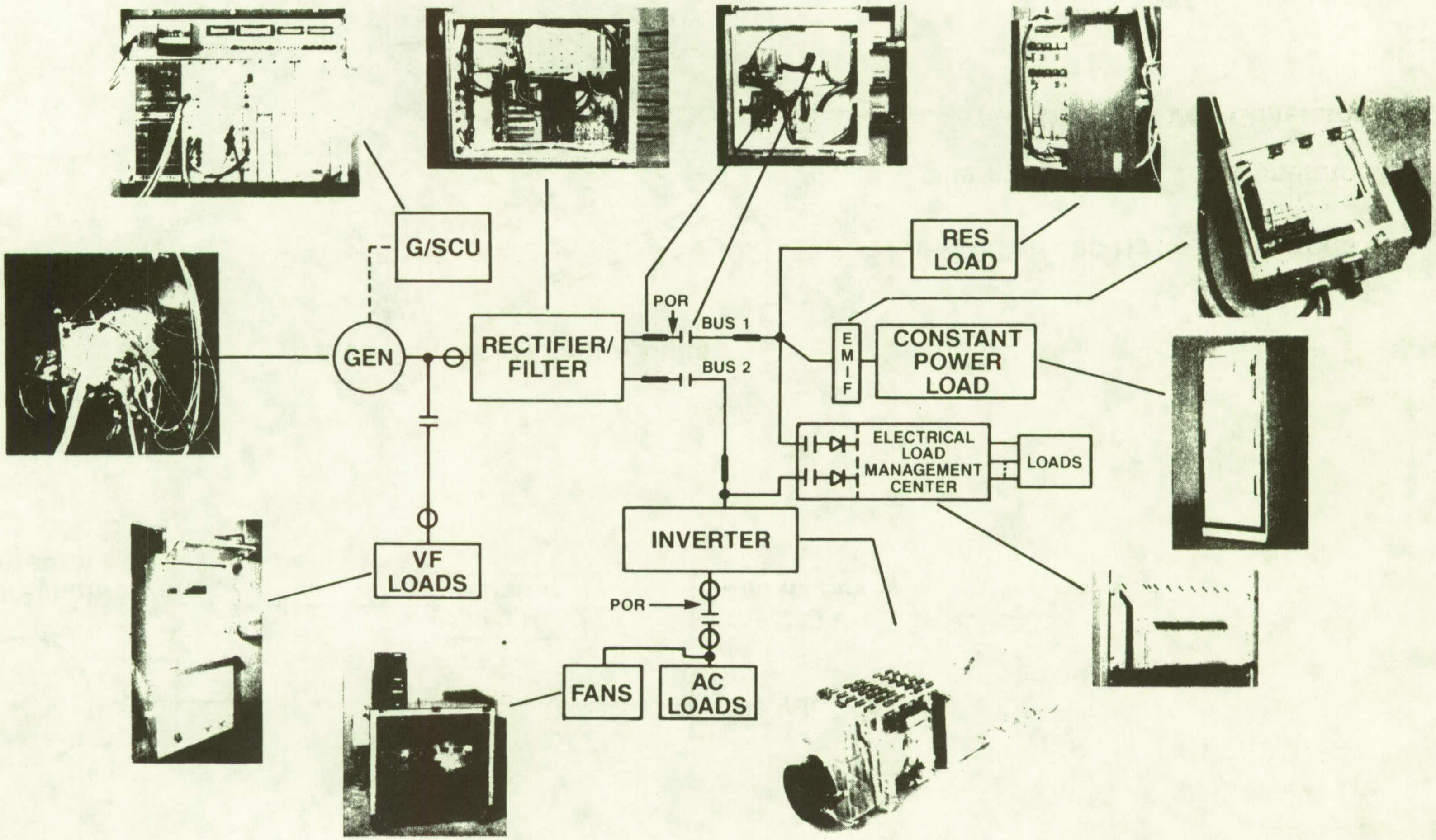
SUNDSTRAND AEROSPACE
Sundstrand Corporation

A 270 Volt DC System With a High Speed Turboalternator Is a Practical Option for Launcher TVC Power, as Shown by

- DC Power System Development
- Progress in Turboalternator Technologies

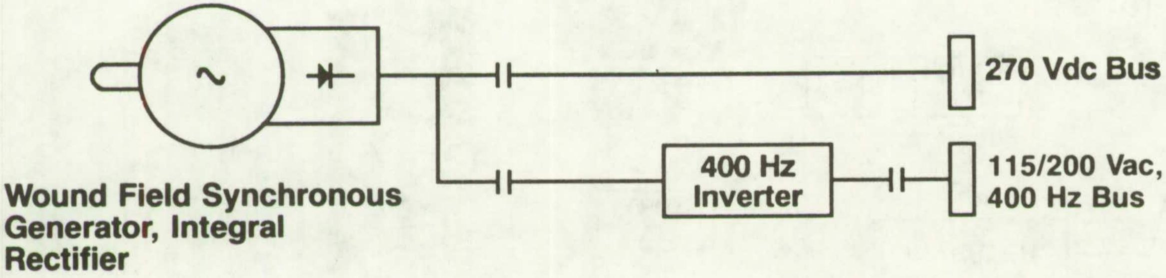
SUNDSTRAND AEROSPACE
Sundstrand Corporation

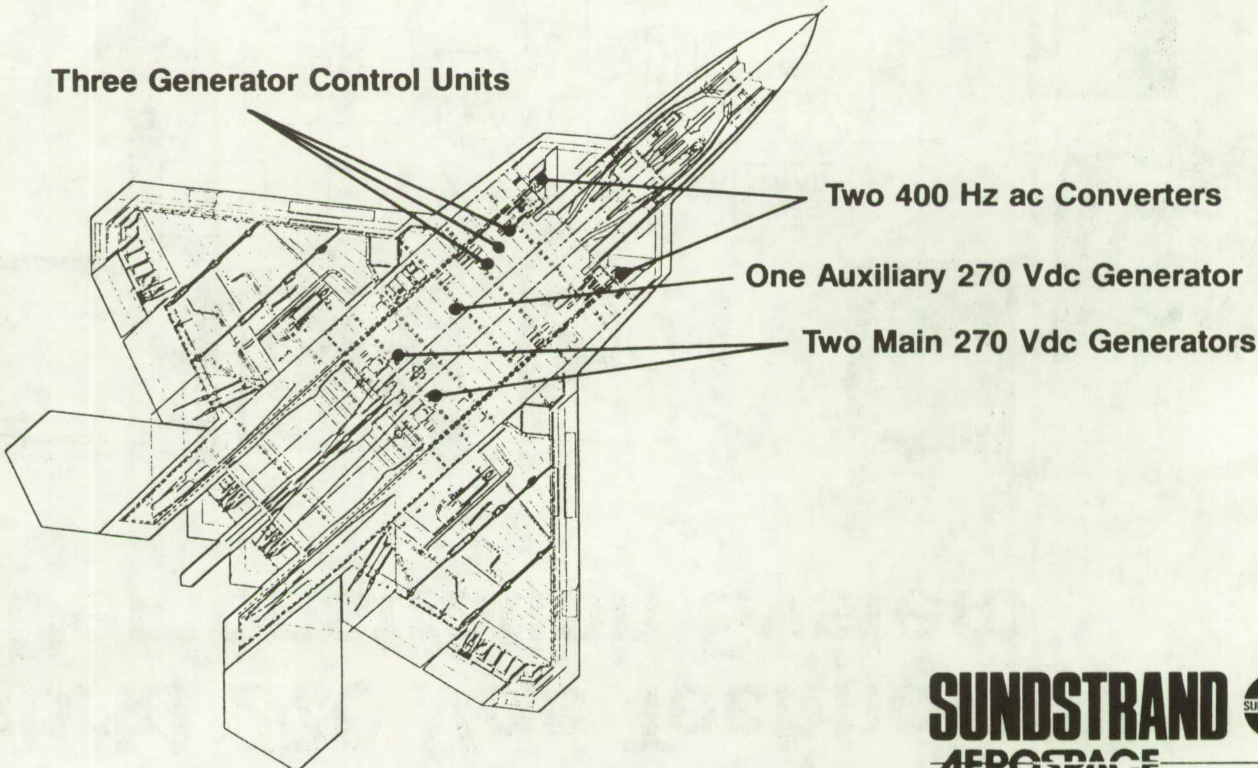
Hybrid 270 Vdc Technology Demonstration System



SUNDSTRAND AEROSPACE
Sundstrand Corporation

F-22 Electric Power System

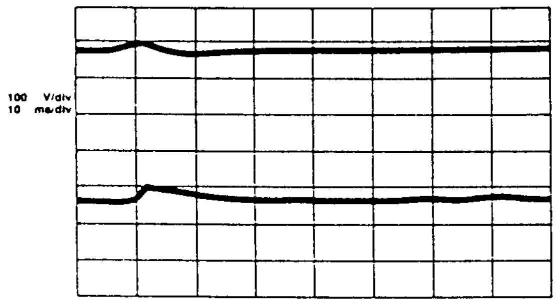




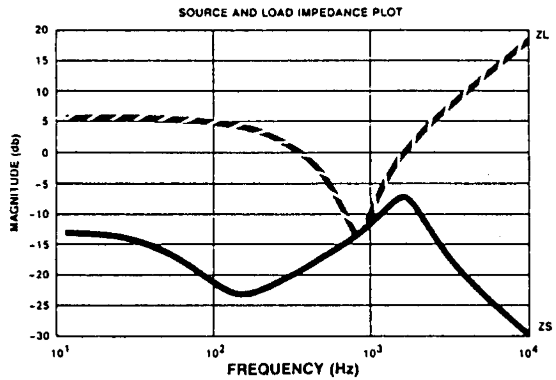
SUNDSTRAND AEROSPACE
Sundstrand Corporation

270 Vdc System Issues

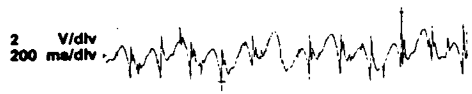
Power System Transients



Power System Stability



Voltage Distortion



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Launcher TVC Power Issues

- Generator/Regulator Architecture
- Conductor Layout
- EMI Suppression and Control

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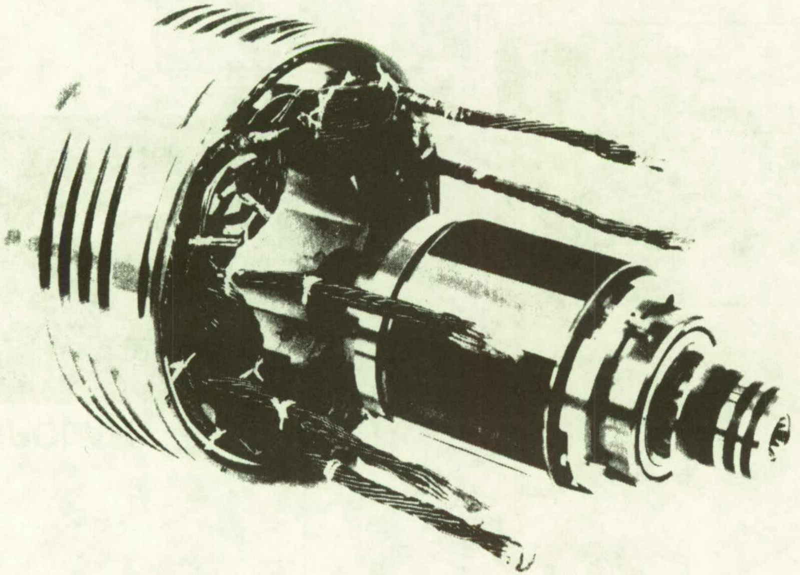
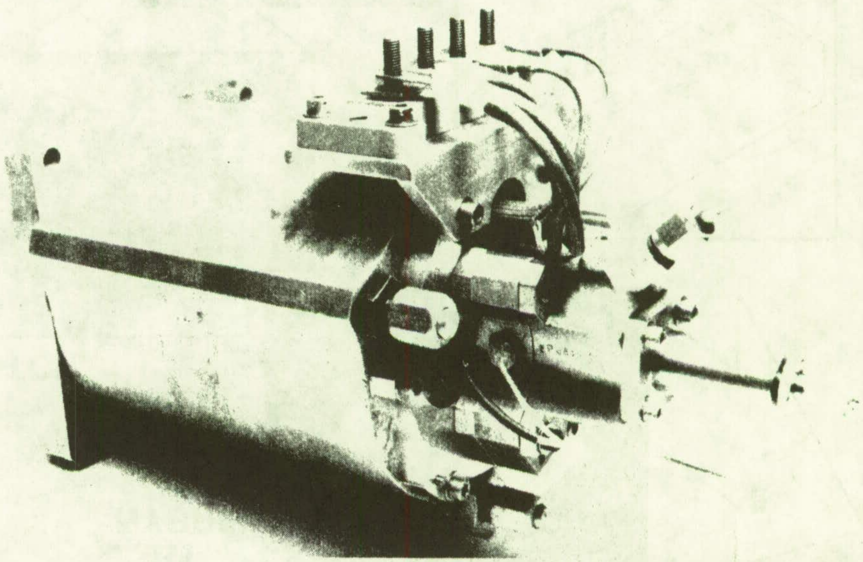
Electromagnetics



Switched
Reluctance



Permanent
Magnet
Brushless

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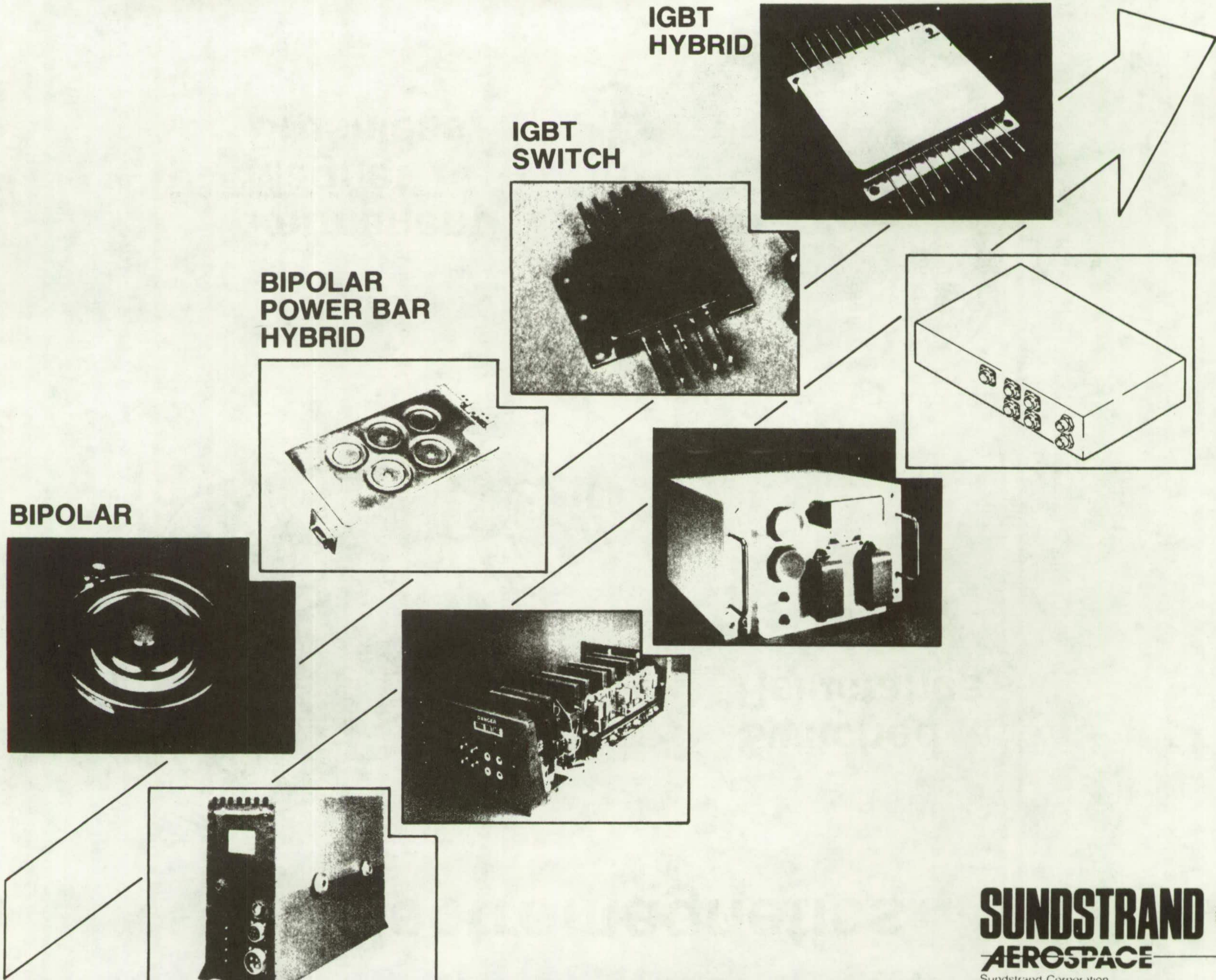
Power Electronics

1983 — 1992



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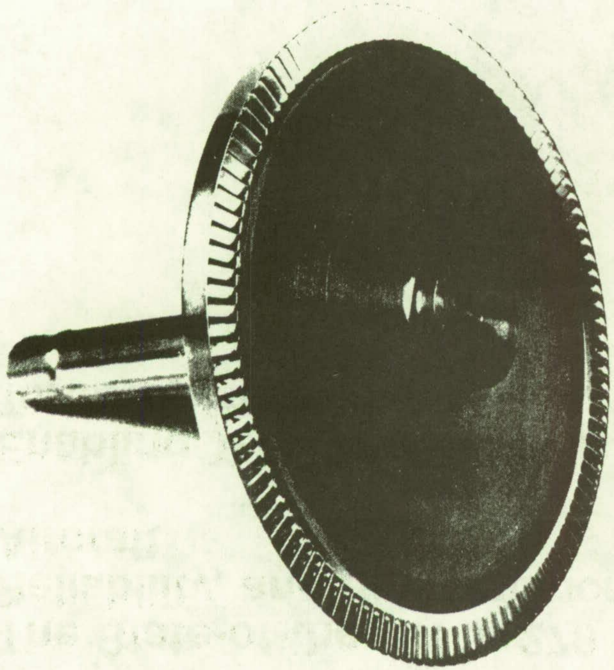
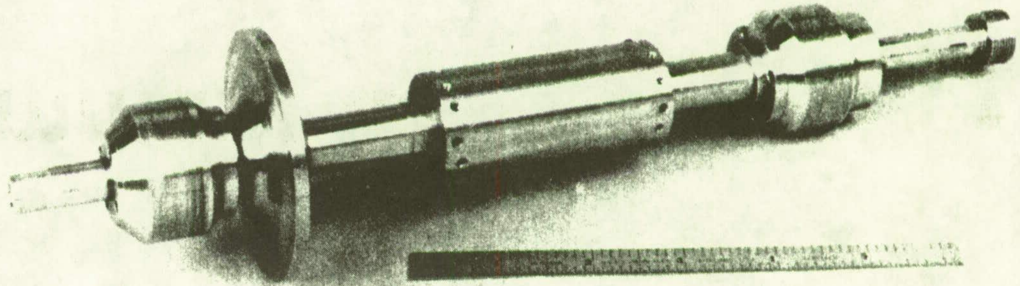
High Speed Machinery



Turbomachinery

High Speed Bearings



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Summary

- The State-of-the-Art in 270 Vdc Power Can Support the Weight, Cost, Reliability, and Performance Goals for New Helicopters and Fighter Aircraft
- Enabling Technologies Exist for Development of Very Densely Packaged Turboalternator Power Sources for Launcher TVC

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Sundstrand Corporation

GH2 Turbo-Alternator

NASA Electrical Actuation Technology Bridging Workshop @ MSFC

9/30/92

John Anderson
(206) 773-0188

BOEING

TVC PSS Options

- Turbo-Alternators
  - GH2
  - H2O2
  - Hydrazine
- Batteries
  - AgZn
  - Bipolar Lithium
  - Advanced AgZn
- Others
  - Fuel Cells
  - Flywheels

TVC PSS Comparisons

	GH2 Turbo-Alt	AgZn Battery	Li/SOCl2 Battery
Ability to handle high peak/average current ratio	high	moderate	moderate
Ability to supply continuous peak power power	high	low	low
Voltage Droop Control	high	moderate	moderate
Reliability	high	high	unknown
Operability (MTBF)	high	TBD	unknown
Test/Checkout Capability	high	moderate	moderate
Technology Maturity	high	high	low
Availability	high	high	low
Safety	high	moderate	low (toxic gas, explosion)
Size (inches)	10 dia x 20 long (3 for 2 engines)	7.5 x 8.3 x 12 (9 for 1 engine)	11 dia x 8 long (2 for 1 engine)
Weight (lbs/engine)	60	405	60
Cost ($K/engine)	225	TBD	TBD

BOEING

GH2 PSS Selection

- Continuous Power Supply
- Peak Power Load Capability
- Voltage Droop Control
- Low Weight
- Test & Checkout
- On Pad Power-up
- Application of Existing Technologies

GH2 PSS Operations Savings

Shuttle Hydrazine APU

Generic Vehicle Function	Hours	People	Man Hours
APU H2O VLVS R&R/Deservice POSU	32.0	5	160.0
APU H2O Deservice/Service	80.0	8	640.0
APU H2O Service Secure	4.0	4	16.0
APU Lube Oil Service POSU	8.0	5	40.0
APU Lube Oil Service	26.0	10	260.0
APU Lube Oil Service POI	8.0	4	32.0
APU Catch Bottle Drain	96.0	23	2208.0
APU Lube Oil Deservice POSU	64.0	10	640.0
APU Lube Oil Deservice	9.0	10	90.0
APU Fuel Valve Resistance Check	40.0	5	200.0
APU Leak and Functional POSU	16.0	10	160.0
APU Leak and Functional	176.0	10	1760.0
APU Leak and Functional POI	48.0	8	384.0
Launch Pad			
Service Auxiliary Power Unit	24.0	34	816.0
Retract RSS	8.0	11	84.0
"Hot Fire" Auxiliary Power Unit	8.0	TBD	
Extend RSS	8.0	11	84.0
Total	655.0		7574.0

NLS GH2 Power Source

Common Core Function *	Hours	People	Man Hours
APU H2O VLVS R&R/Deservice POSU			
APU H2O Deservice/Service			
APU H2O Service Secure			
No Equivalent Function			
No Equivalent Function			
No Equivalent Function			
No Equivalent Function			
No Equivalent Function			
No Equivalent Function			
No Equivalent Function			
APU Leak and Functional POSU	16.0	10	160.0
APU Leak and Functional	176.0	10	1760.0
APU Leak and Functional POI	48.0	8	384.0
No Equivalent Function			
No Equivalent Function			
No Equivalent Function			
No Equivalent Function			
Total	240.0		2304.0

* Using Gaseous Hydrogen

Possible Saving of 415 Processing Hours

Possible Saving of 5270 Processing Man Hours

Generic Vehicle Data Extracted from Operationally Efficient Propulsion System Study (OEPSS) Data Book.
Functional Data based on STS Orbiter (3 Main Engine System) Processing Operations and Maintenance Instructions.

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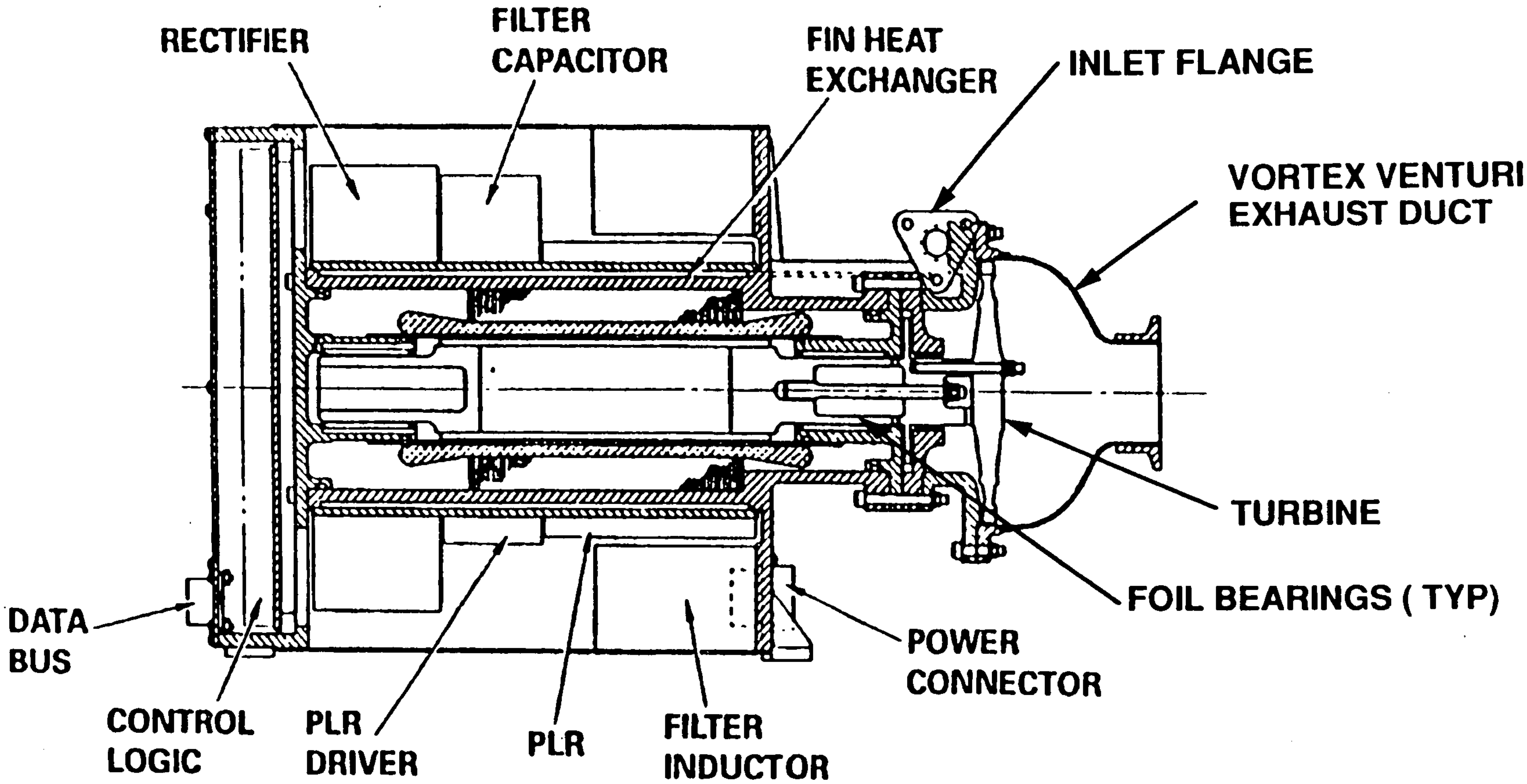
GH2 Turbo-Alternator



90 hp	10 dia x 20 long	58 lbs
45 hp	TBD	41 lbs

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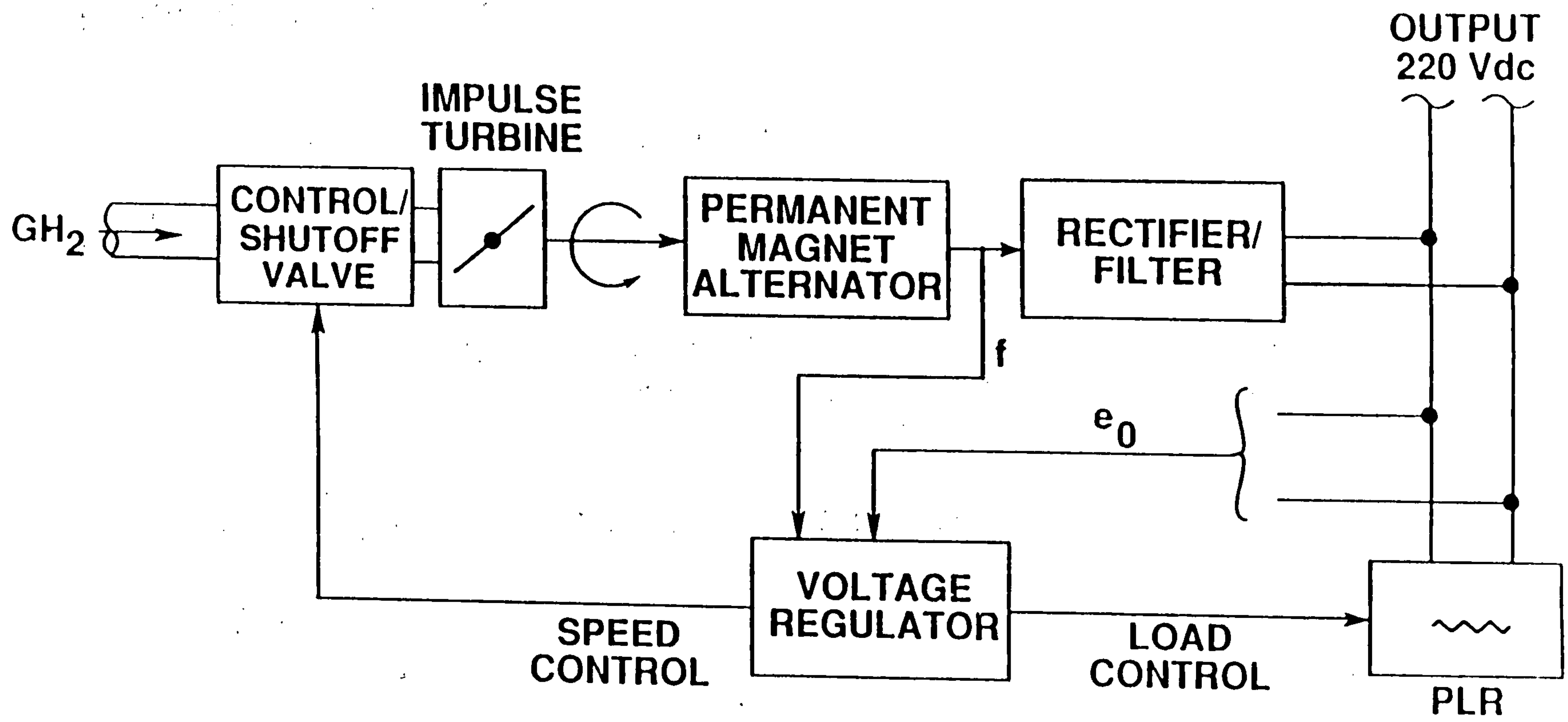
GH2 Turbo-Alternator Block Diagram



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GH2 Turbo-Alternator Voltage Regulation

Power Output

- Regulation for steady state and increases in load current provided by turbine speed control
- Regulation for decreases in load current providedby PLR (transient) and turbine speed (steady state)

Regeneration

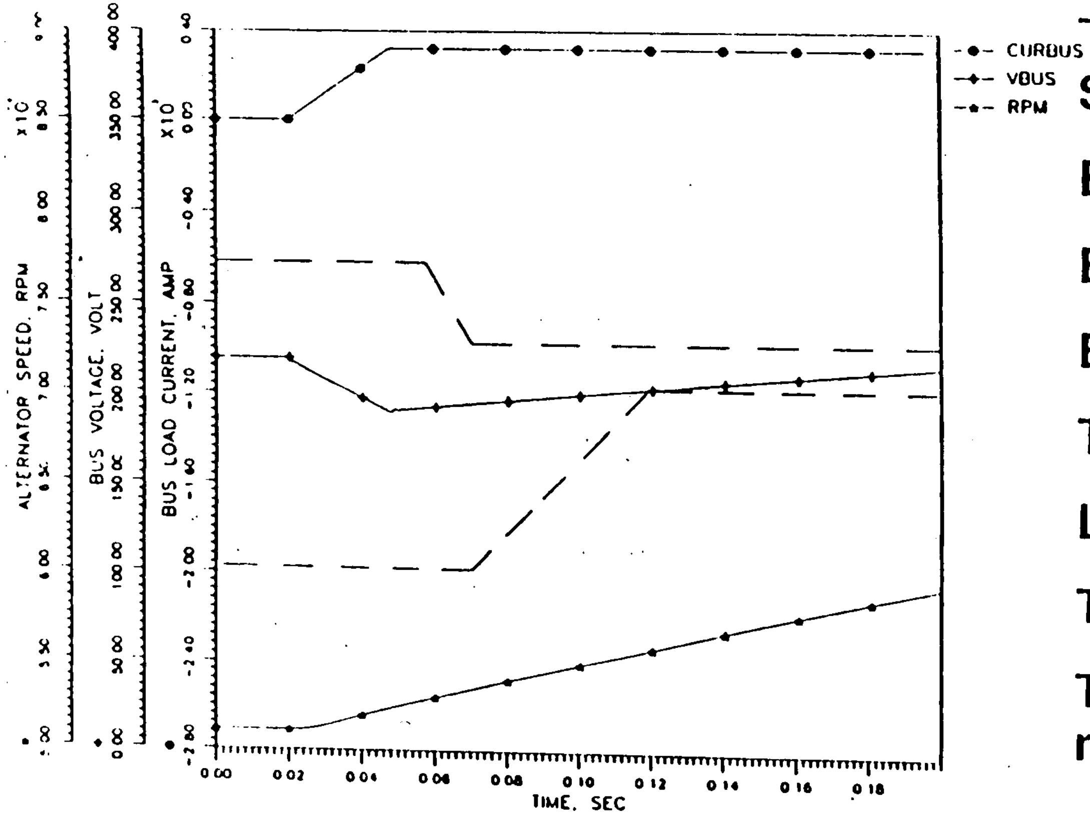
- Regulation provided by PLR

Output/Internal Fault

- Turbine shut down limits fault current to safe duration

GH2 Voltage Response Opposing load

0 to 320 A current ramp



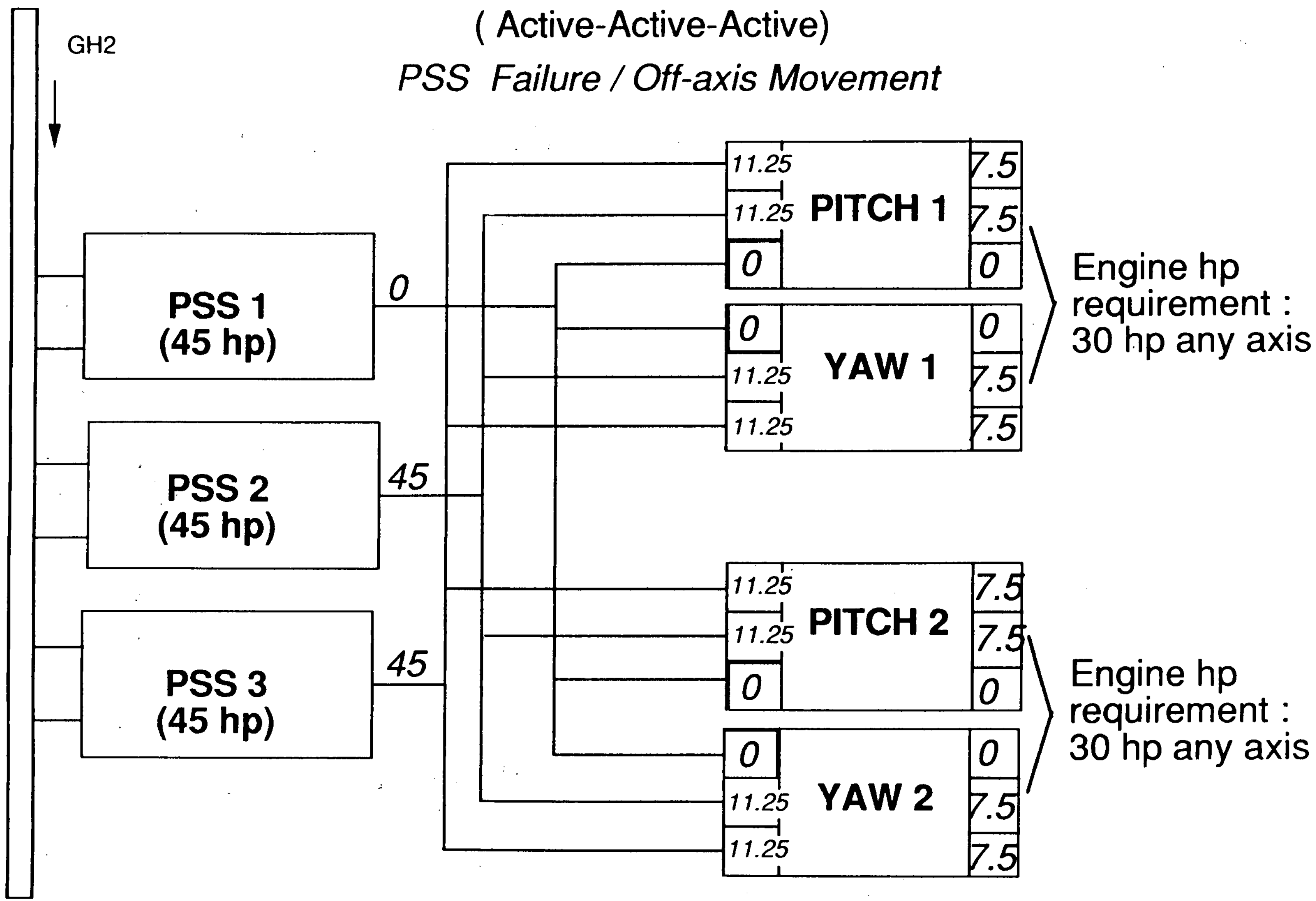
Steady-State Operating Condition		
Supply pressure	2500	psia
Exhaust pressure	515	psia
Bus current	320	A
Bus voltage	217	V
TVC power	93.1	Hp
Load resistor power	0	kW
Turbine speed	59450	rpm
Turbine mass flow rate	0.36	lb_m/s

----- MIL-STD-704D voltage limits scaled for 220V

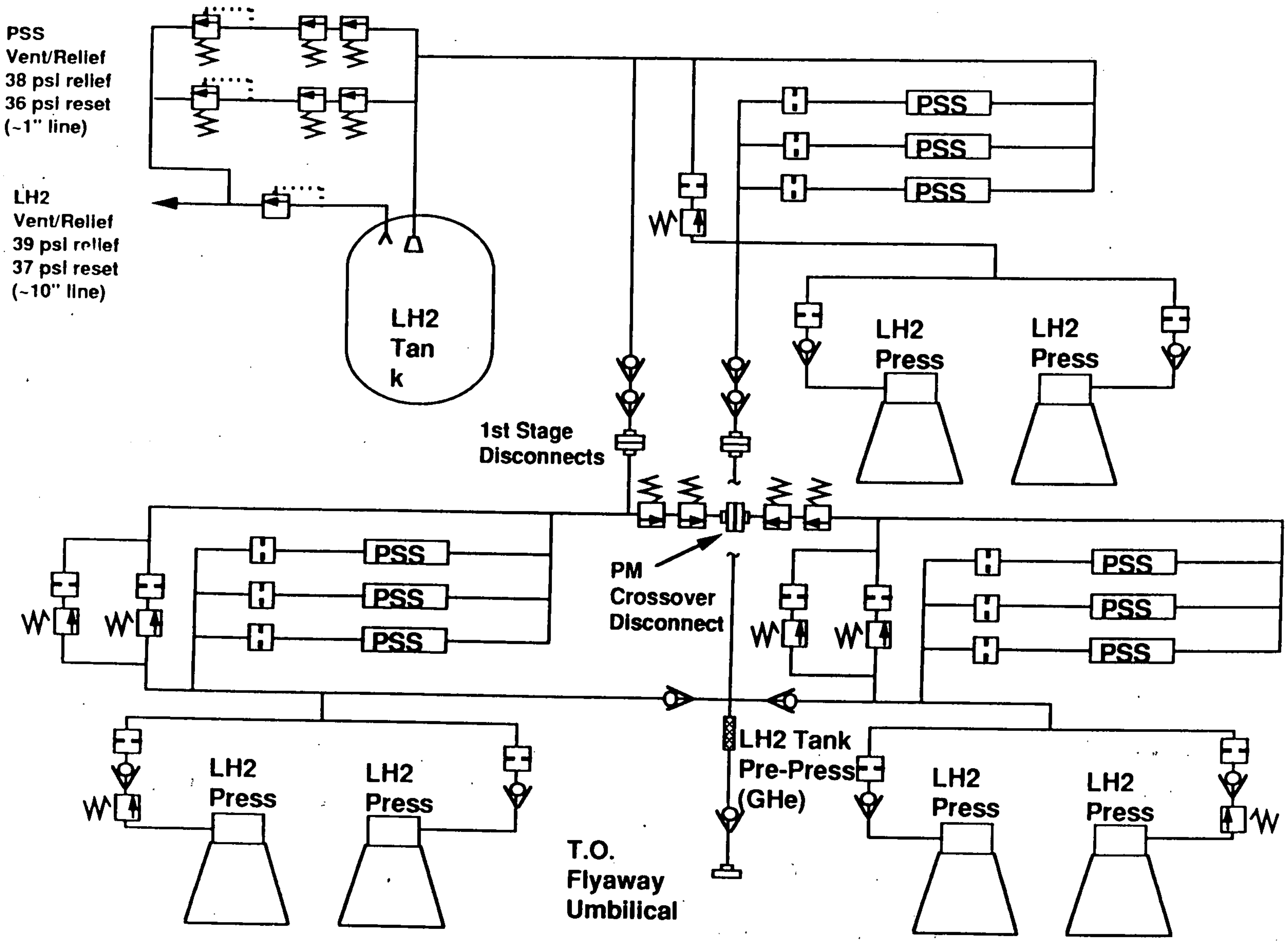
GH2 PSS Distribution

(Active-Active-Active)

PSS Failure / Off-axis Movement



GH2 System Schematic



GH2 Turbo-Alternator ADP Focus

Issue	SEP 92 GHe Demo	Oct 92 GH2 Design	FY 93 GH2 Fab/Test
Voltage Control	X	X	X
GHe Operation	X	X	X
GH2 Operation		X	X
GH2 Materials Compatibility		X	X
Foil Bearing GH2 Operation		X	X
Control Valve Performance		X	X
GH2 Static Sealing		X	X
PLR thermal Management		X	X
Size		X	X
Weight		X	X
Cost		X	

BOEING

TVC Power Source Design Drivers

- Voltage Level / corona effects
- Duty Cycle Margin / available energy
- Voltage Droop Control / actuator performance
- Distribution & Redundancy / single-fault-tolerant, fault isolation
- Weight / total system
- Test & Checkout / operability
- Prelaunch Power-Up Capablity
- Technology Maturity

ELECTRICAL ACTUATION

TECHNOLOGY BRIDGING PROGRAM

POWER SOURCE SIMULATOR

Presented at

ELA & Power Systems Workshop

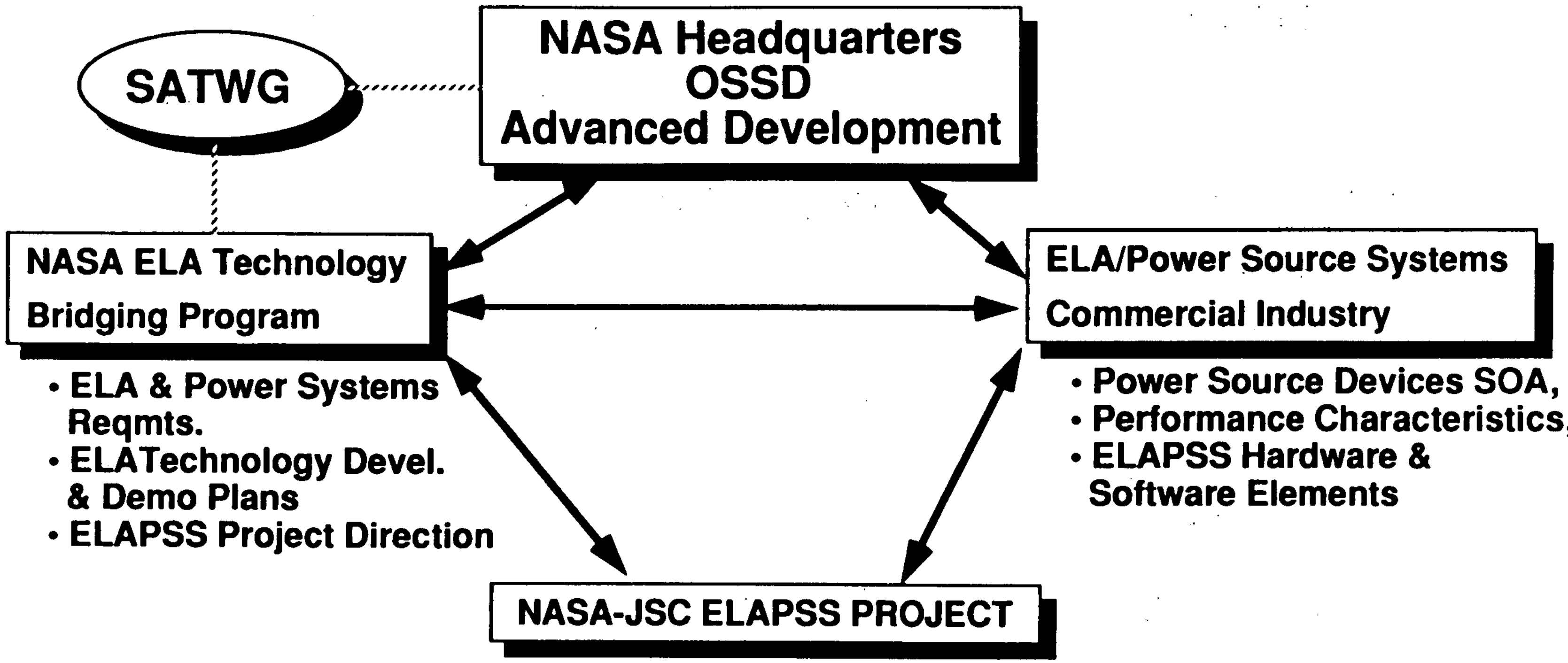
NASA - MSFC

September 30, 1992

NASA-JSC: Don Brown

Lockheed ESC: Mike Bradway

ELA-TB & ELAPSS Principals & Roles



- ELA & Power Systems Reqmts.
- ELATechnology Devel. & Demo Plans
- ELAPSS Project Direction

- Power Source Devices SOA,
- Performance Characteristics,
- ELAPSS Hardware & Software Elements

- ELAPSS Project Mgmt.,
- ELA-TB Program Interface,
- System Engrg. & Integration,
- H/W & S/W Procure. & Devel. ,
- ELAPSS Assembly & Test

Potential ELA Technology Space Applications

ELA Space Applications	Actuator Size
Space Transfer Vehicles (PLS, ACRV)	.5 - 5.0 kW
Propellent Control Valve	5 kW
Orbiter Nose-Wheel Steering	10 - 12 kW
Commercial ELVs (Atlas, Titan, Delta)	12 - 20 kW
Obtiter Main Engine (SSME)	23 kW
Orbiter Elevons	28 kW
Space Shuttle SRB Thrust Vector Control	83 kW (pk)
NLS Thrust Vector Control (configuration dependant)	50 - 70 kW
Heavy Lift Launch Vehicle	70 - 120 kW
Planetary Surface Vehicles (Rover, Digger, etc.)	5 - ? kW

Baseline ELA Requirements for NLS and SRB

Requirement	NLS TVC Reqmts.	SRB TVC Reqmts.
Peak Power:	59 kW	83 kW
Base Power	5.7 kW	6.8 k
Average Power	8.2 kW	33.1 kW
Voltage	200 Vdc	200 Vdc
Pulse Duration	.5 sec.	1.5 sec.
Pulse Frequency	10 sec.	4.25 sec.
Energy / Pulse	7.4 Wh	32 Wh
Max. No. of Pulses	54	29
Operating Time	9.5	2.1
Total Energy	1.3 kWh	1.16 kWh

ELA System Power Source Alternatives

- A variety of ELA systems and requisite power source combinations are being considered for many different applications (launch vehicle TVC, PCV, Orbiter flight control, steering, braking, GSE fluid control, planetary surface equipment)

- Each ELA and system application means unique power characteristics to maximize system operation and efficiency, while minimizing costs

- ELA power source alternatives include:
  - high power density batteries
  - advanced fuel cells
  - gH_2 turbine-driven alternators
  - flywheel energy storage devices

- Each power source type is viable and appropriate for a specific ELA application and set of program/vehicle constraints

ELAPSS Purpose & Scope

- The ELA Technology Bridging Programs integrated ELA & power systems test & demonstration plans require power output capability which characterizes all power source options for the variety of ELA applications

- Acquisition or development of actual power source devices is not practical within ELA-TB Program budget and schedule constraints

- The ELAPSS will provide a programmable power source emulation capability to meet all NASA ELA application/system test & demonstration needs

- One ELAPSS can be developed to emulate the defined operating characteristics of any power source using commercially available hardware and applications software

ELAPSS Purpose & Scope (cont'd.)

- A modular design will allow the ELAPSS to be reconfigured to support multiple ELA system sizes, redundancy schemes, and integrated ELA/power system performance and fault testing

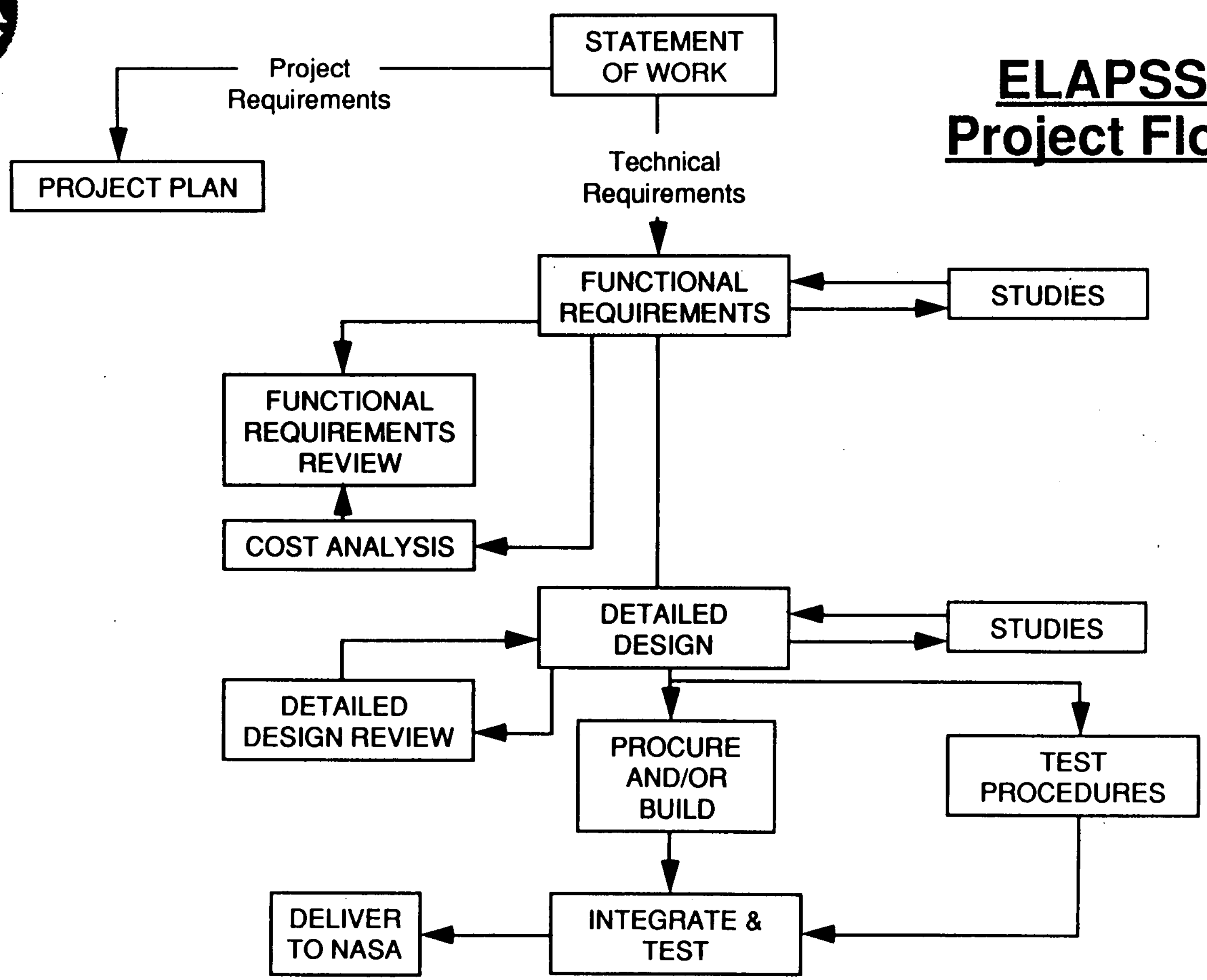
- The ELAPSS will provide a permanent power source simulator capability for use on current and future NASA programs

- The ELAPSS will be a portable piece of NASA GSE for use at any NASA center with the facility to support it

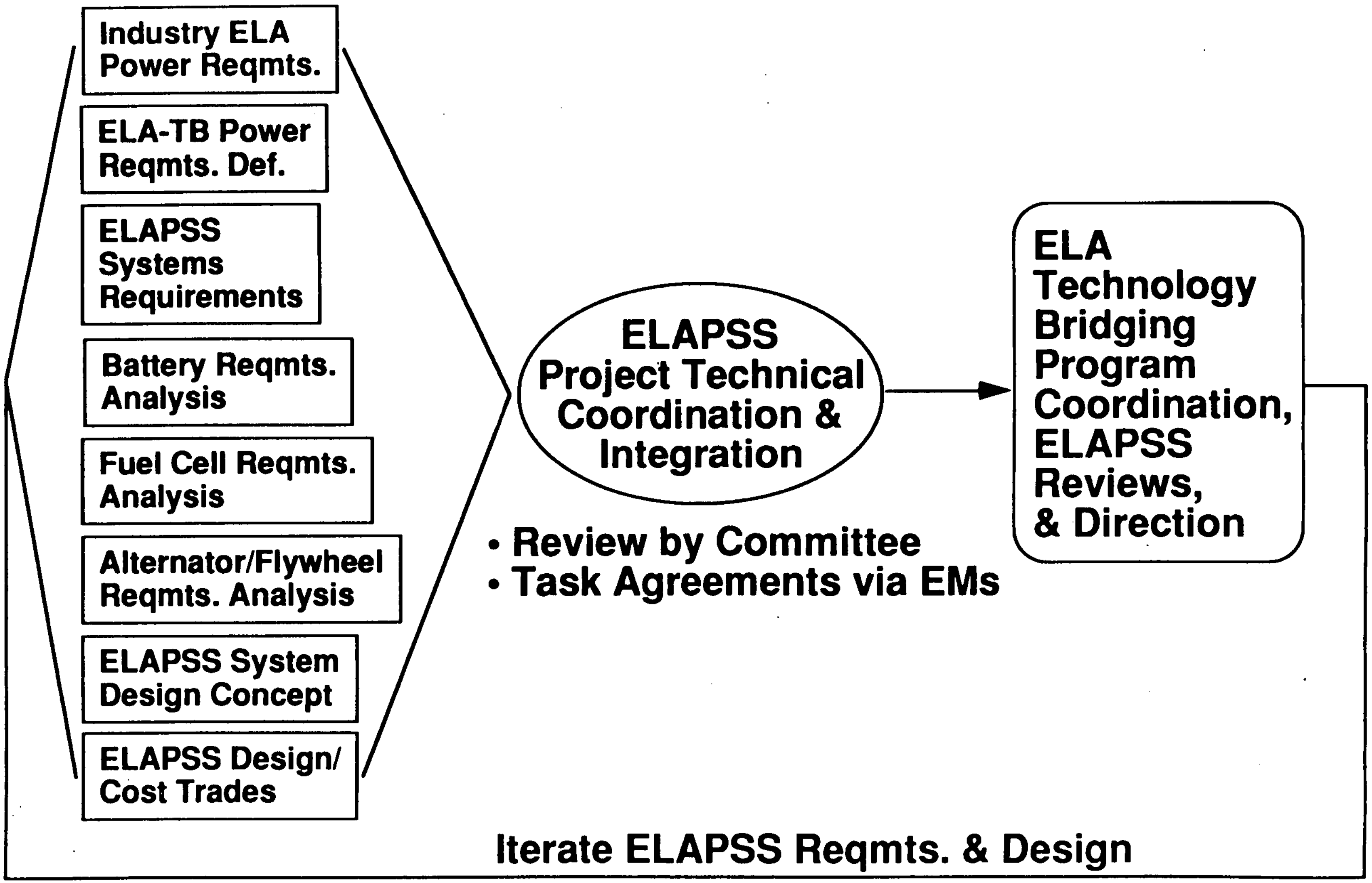
- The ELAPSS will be developed with commercial components for more timely development & use, more cost effective replication, and future expansion of power source emulation capability

- The ELAPSS allows very robust power degradation and fault testing capability via automated test sequences or manual commands from an operator control console

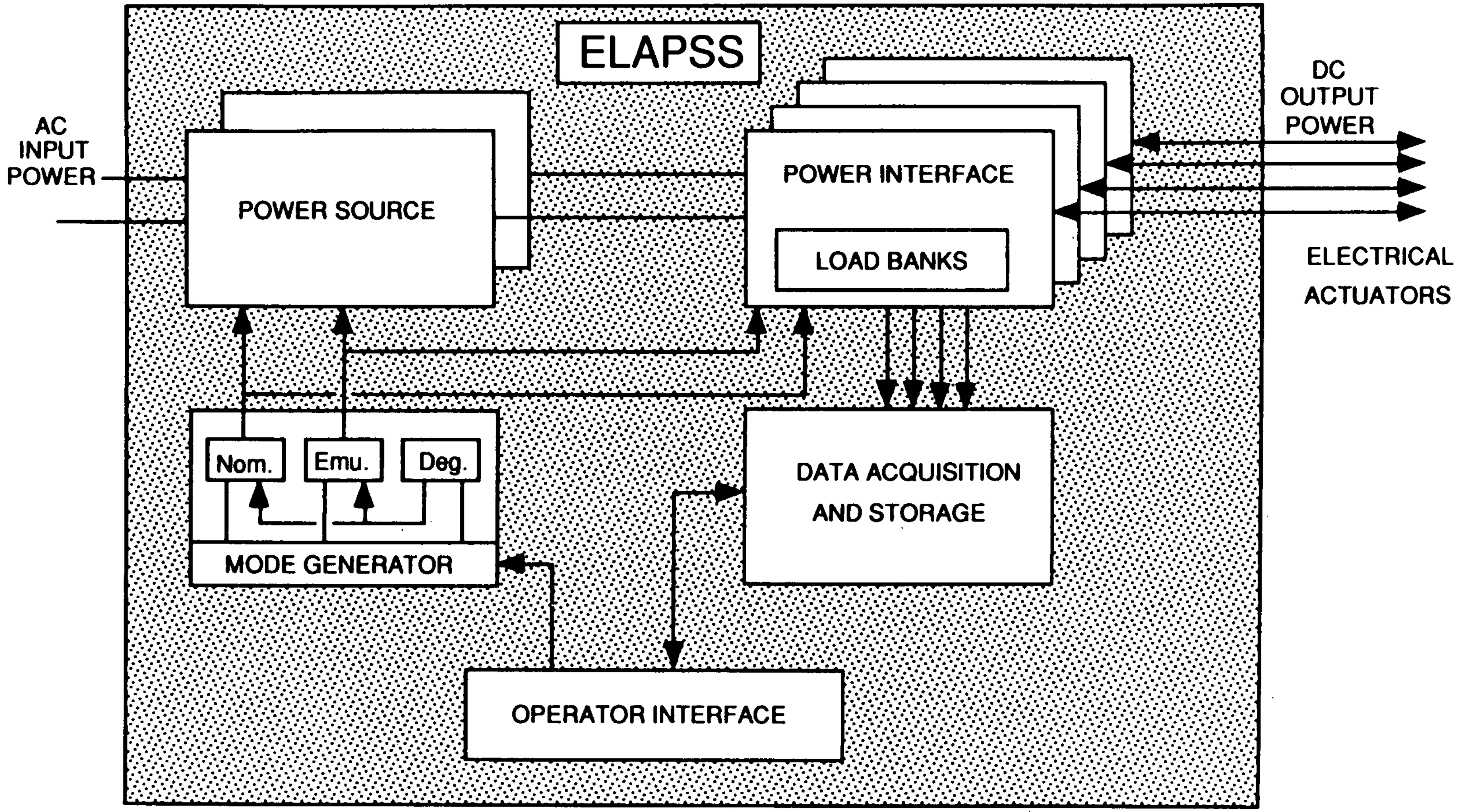
ELAPSS Project Flow



ELAPSS Development Approach



ELAPSS Functional Diagram



ELAPSS FUNCTIONAL BLOCK DIAGRAM

Electrical Actuation Power Source Simulator (ELAPSS)

REQUIREMENTS

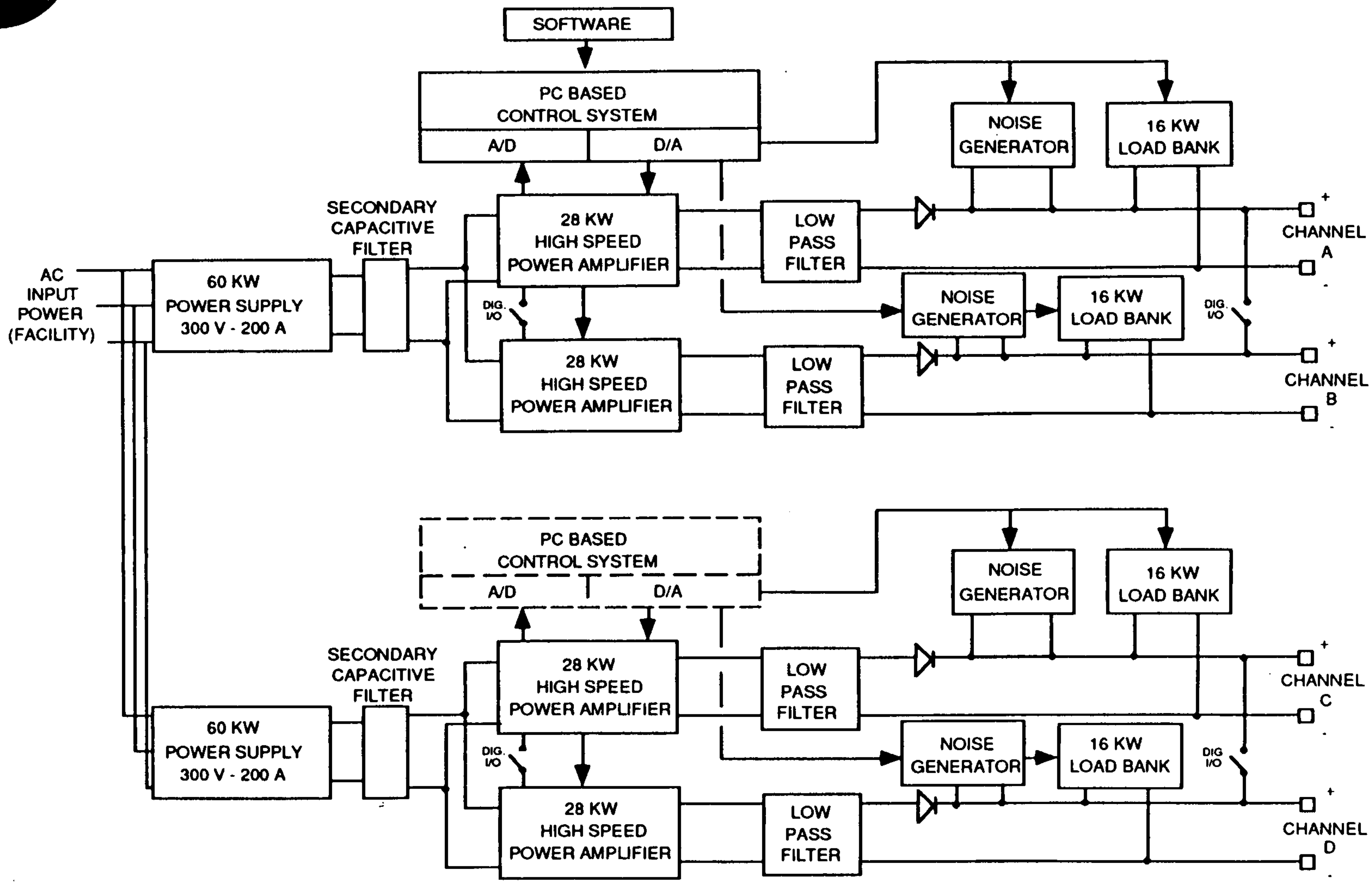
* ELAPSS will provide power for a variety of non-flight Electrical Actuators - up to 120 kW at 28, 120, 200 and 270 Vdc.
* ELAPSS will be able to provide nominal power or emulate Batteries, Fuel Cells, Turbo Alternators and Flywheels
* ELAPSS will be able to provide off-nominal power in either nominal or emulation power modes. Off-nominal power could be EMI injection, power source faults and line faults.
* ELAPSS will be able to absorb returned energy from the ELA
* ELAPSS will be able to support redundant ELA testing

BASIC DESIGN CONCEPT

The proposed Electrical Actuator Power Source Simulator will have following basic components:

- A programmable switch-mode DC Power Supply
- PWM Power Amplifiers
- A microcomputer based instrumentation and control system

JSC Navigation, Control & Aeronautics Division



ELAPSS FOUR CHANNEL HARDWARE CONFIGURATION

ELA Technology Bridging Program Power Source Simulator

DC POWER SUPPLY:

The DC Power Supply provides variable dc power for the power amplifiers from the utility power. To insure that the system output will respond as fast as the amplifiers are capable, it has a large capacitor bank at the output terminal. The DC power supply is separate module in the ELAPSS system and hence, can be reconfigured easily.

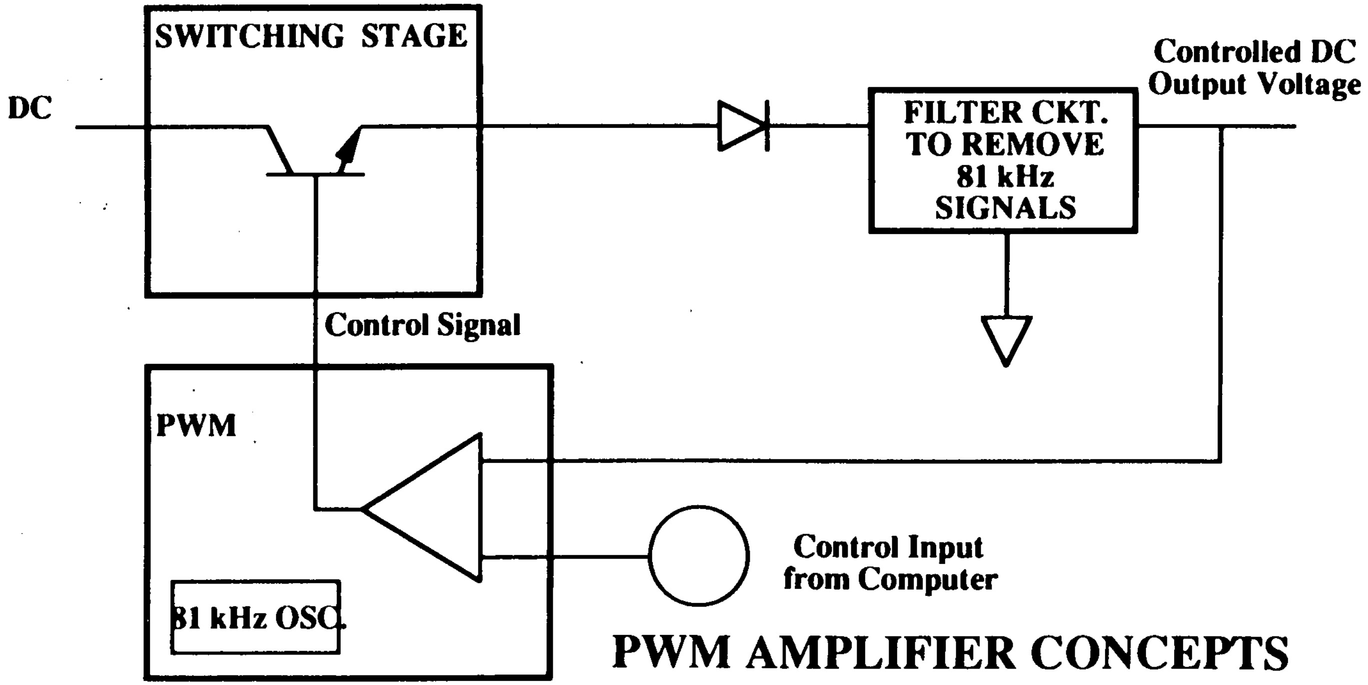
PWM POWER AMPLIFIERS:

These are high power Pulse Width Modulated switching amplifiers that can be designed as master-slave system to allow paralleling multiple modules to meet high power need. Each amplifier contains power modules consisting of a full H-bridge switching stage. The input to the power module is a 81 kHz control signal. The output of each power module is a series of power current pulses at 81 kHz rate whose width is proportional to the analog control signal.

PWM POWER AMPLIFIERS (Contd):

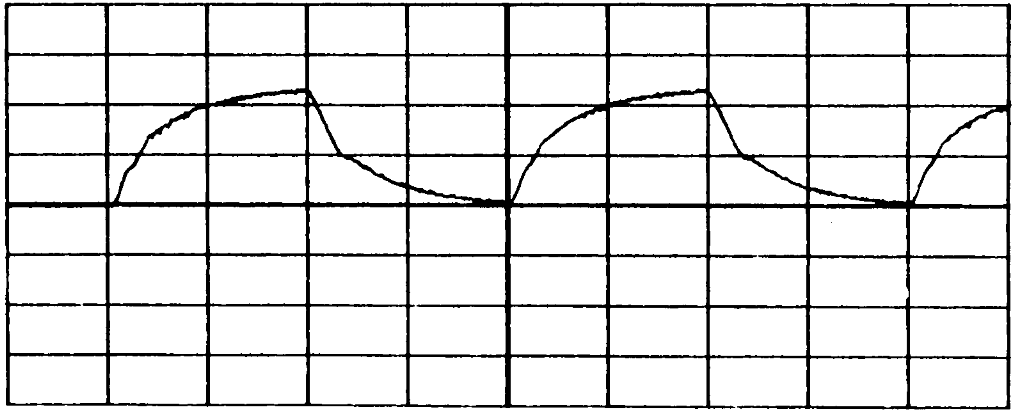
The PWM output is then applied to a low pass filter to eliminate the 81 kHz and its harmonics. The resultant output is DC with little ripple content.

The PWM switchmode type of amplifiers is important for this design because it allows a large output voltage range without dissipating excessive amounts of heat.

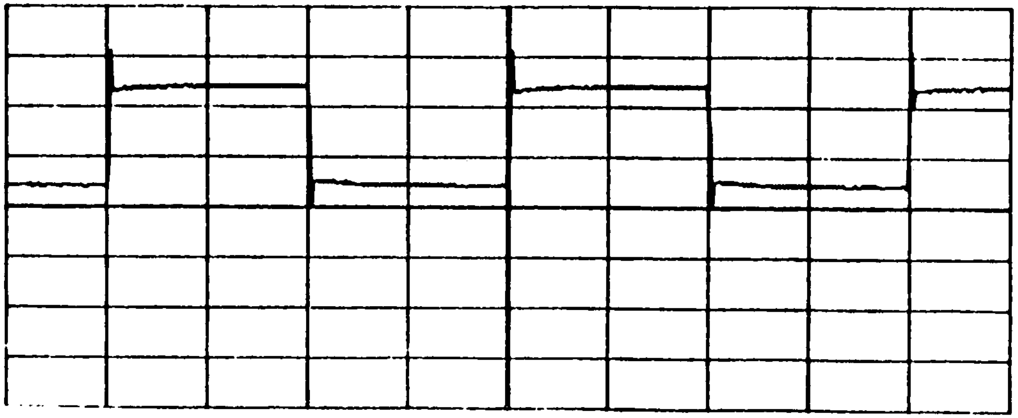


PWM AMPLIFIER CONCEPTS

Power Simulator (without PWM Amp) Output Transisent Response with Step Control Input



Power Simulator (with PWM Amp) Output Transisent Response with Step Control Input



MICROPROCESSOR CONTROLLER:

This consists of an industrial PC and instrumentation and control modules. The system load current is monitored by current sensor and processed by an analog to digital converter (ADC). The data read from the ADC module is used by the microprocessor to calculate the voltage control signal for proper simulation output. This control signal is then sent to the power amplifiers via a digital-to-analog converter.

OFF-NOMINAL OPERATION

IN ADDITION TO THE BASIC SYSTEM COMPONENTS, THE FOLLOWING MODULES ARE REQUIRED FOR DEGRADED OR OFF-NOMINAL MODE OF OPERATION:

- NOISE GENERATOR:

  A signal generator and wide band amplifiers may be used to inject noise into the output line to degrade output power.

- LOAD BANKS:

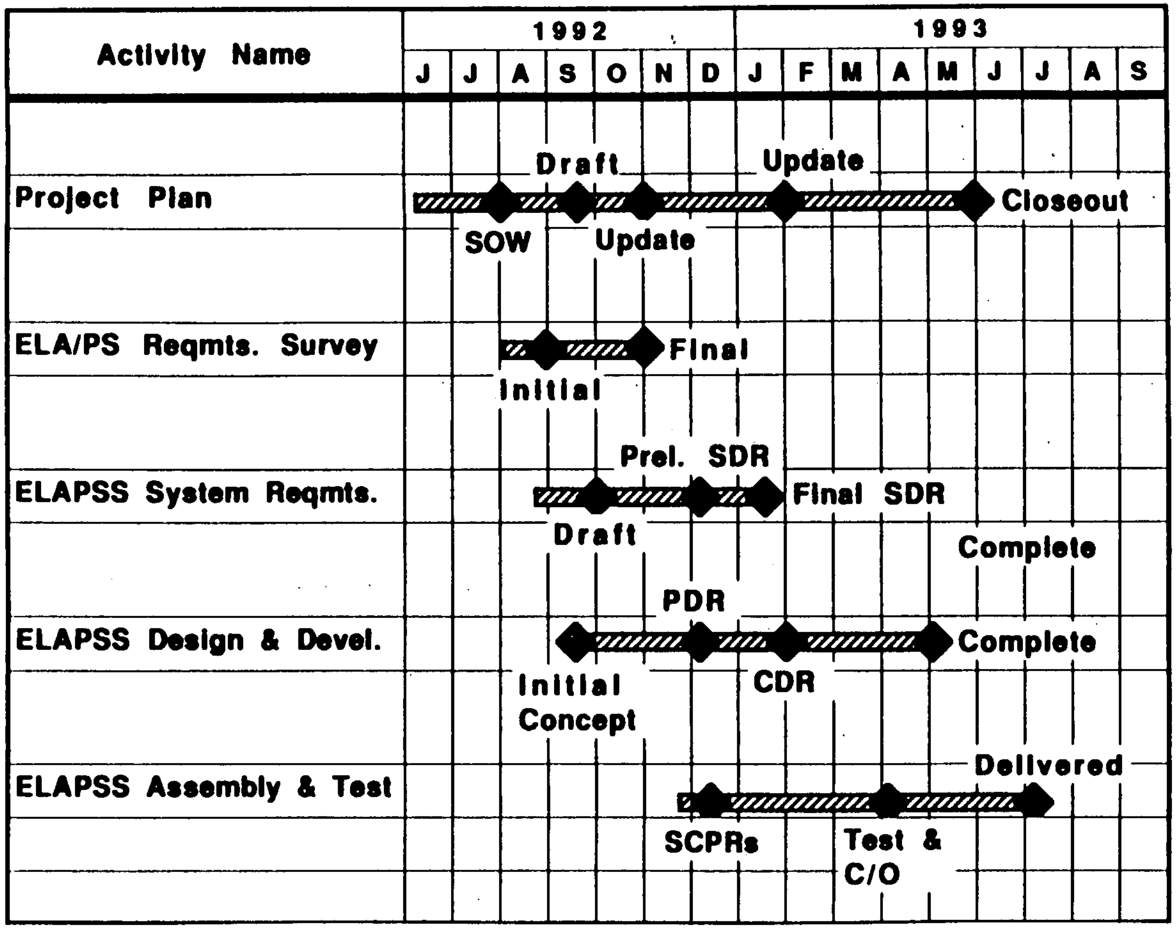
  These are active control MOSFET off the shelf modules which act as current sinks to absorb return energy from the ELA under test. These devices are turned on by the micro-computer controller.

Both the noise generator and the load banks are commercially available modules.

ELAPSS Design Drivers

- High power output capability:
  - 60 - 90 kW TVC requirements for NLS, ASRM (SRB)
  - 90 kW peak power required to meet SRB TVC ELA reqmts. (SRB start transient and roll manuever load profiles)
- Dual & Quad redundant ELA system test capability
  - NASA-MSFC building a quad 60 kW system (4 - 15 kW motors)
  - NASA-LeRC building dual 60 & 80 kW systems
- EMI characteristics of the power bus with switching loads
- Return energy absorption capability (from each channel)
- ELA power transients (engine start, roll manuever) exceed the response time of fastest programmable power supply available

ELAPSS Project Schedule (FY'92)



ELAPSS Value To NASA

- Supports verification of any NASA ELA systems performance & fault tolerance/redundancy with appropriate representative power source emulation

- A programmable portable ELAPSS capability supports multiple ELA applications testing at any NASA site with supporting facility

- ELAPSS provides a permanent resource to NASA - a link in the chain of end-to-end integrated power/avionics advanced development and test capability for any vehicle/surface system

- Modular, commercial ELAPSS design provides multiple ELA/power system testing flexibility, and allows easy reconfiguration, expansion or replication as required

- Supports the NASA "bridging" concept - new way of doing business
  - resource sharing among centers & programs

SESSION VII

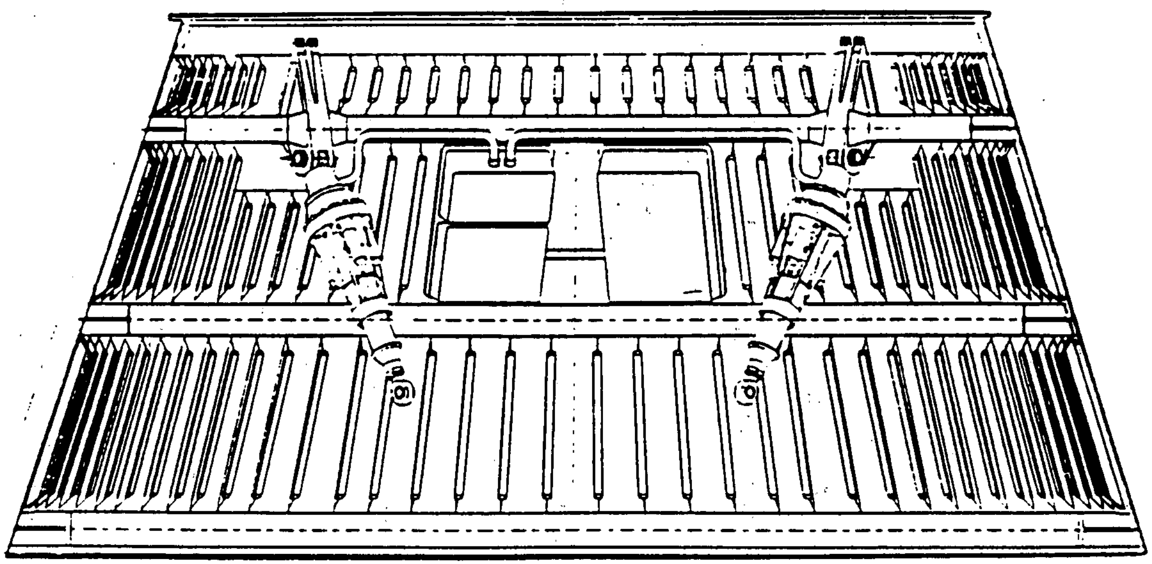
ELA OPERATIONS

September 29, 1992

ELECTRIC ACTUATION

TECHNOLOGY BRIDGING PROJECT WORKSHOP

STS HYDRAULIC VS. ELA OPERATIONS SRB ASSESSMENT



(ELECTRIC SRB AFT SKIRT CONCEPT)

Carey M. McCleskey, NASA/KSC
Haley W. Rushing, ASSI/KSC

WHY AN ELA OPERATIONS TEST BED?

IF A ***CONCURRENT ENGINEERING*** APPROACH TO DESIGN IS TO BE USED, THE LAUNCH SITE OPERATIONS CUSTOMERS WILL NEED TO GAIN ***KNOWLEDGE, SKILLS*** **AND** ***ABILITIES*** IN THE FOLLOWING AREAS:

1. SKILL IN HANDLING HIGH POWER BUSSES

   - SIGNAL MEASUREMENT BETWEEN LRU'S
     GSE REQUIREMENTS & CHARACTERISTICS
   - SWITCHING AND BUS REDUNDANCY/ISOLATION CHARACTERISTICS

2. KNOWLEDGE OF POWER SOURCE CHARACTERISTICS
   - BATTERY HANDLING AND MAINTENANCE
   - FLYWHEEL OPERATION

3. ABILITY TO HANDLE PERSONNEL SAFETY ISSUES

   - BATTERIES
   - HIGH VOLTAGE LINES

4. KNOWLEDGE OF ACTUATOR OPERATION

   - LOCKING OPERATION AND CHARACTERISTICS
   - ACTUATOR INITIALIZATION
   - GENERAL OPERATING CHARACTERISTICS (CURRENT MONITORING / TORQUE EQUALIZATION / VELOCITY SUMMING)

5. EXPERIENCE IN SYSTEM-LEVEL ISSUES

   - DATA MANAGEMENT
   - FAULT MANAGEMENT
   - ENERGY MANAGEMENT (CHARGE/DISCHARGE CYCLES)

Agenda

- Motivation
- SRB TVC Ops Study Results & Video
- Future Plans

Motivation

- **Operational experience with Shuttle**
  - Heavy servicing and deservicing requirements
  - Replacement often difficult
  - Heavy infrastructure overhead
    - Facility
    - Ground Support Equipment
    - Toxic Commodities

- **Objective**
  - Identify Life Cycle Cost of Current Technology
  - Conduct specific one-for-one trades with electric actuation technology Life Cycle Cost opportunities

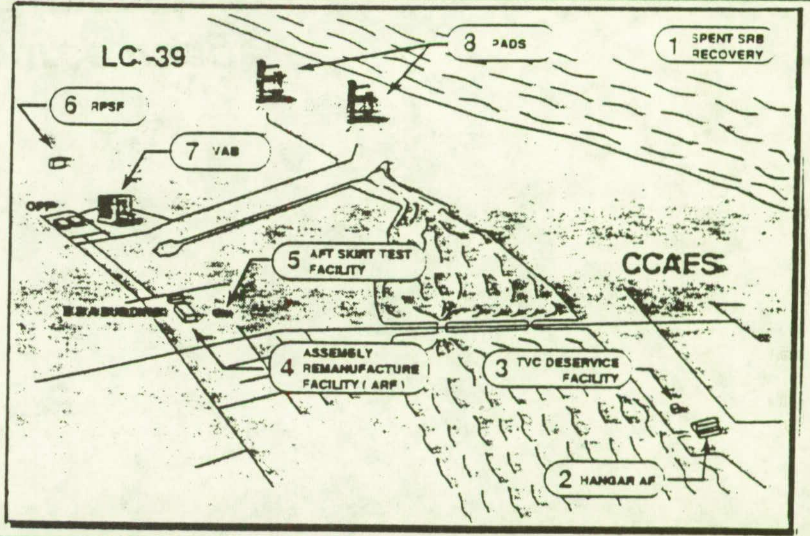
- **Flight Control Candidates for study:**
  - Orbiter (APU/Hyd - Aero/TVC/Prop/Ldg-Decel)
  - SRB Thrust Vector Control System

HYDRAULIC VS ELECTRIC LIFE CYCLE IMPACT

OPERATIONAL BENEFITS SUMMARY

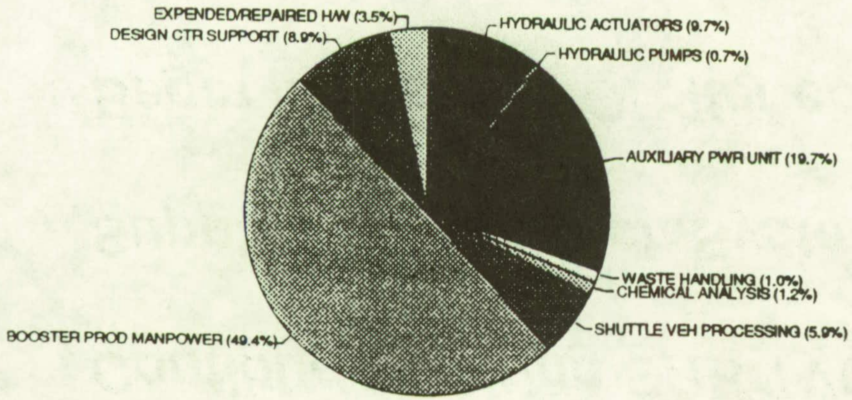
- *REFURBISHMENT COSTS APPROX 2/3 REDUCTION*
- *REFURBISHMENT/CHECKOUT TIME 3/4 REDUCTION*
- *8400 SQ FT REDUCTION IN FACILITY REQUIREMENTS (+ CLEAN ROOM + FLUID SERVICES)*
- *HUNDREDS AND HUNDREDS OF GSE ITEMS ELIMINATED - VERY FEW INTRODUCED*

SRB TVC WORK FLOW/SEQUENCE



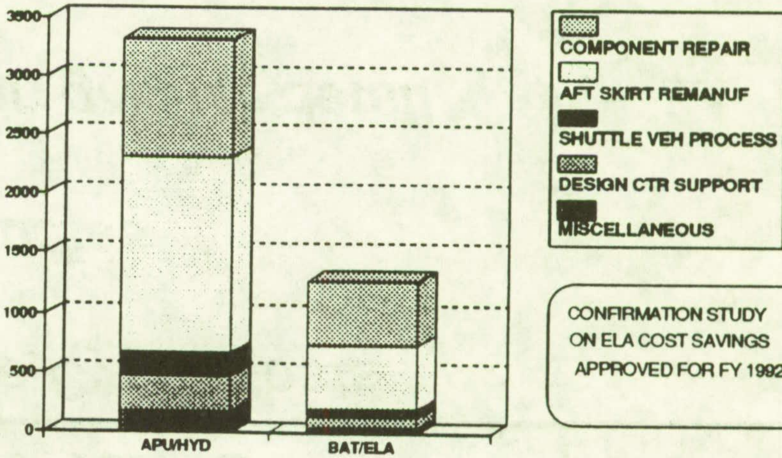
SRB TVC LIFE CYCLE COST ELEMENTS

(System Costs = $ 3.3M Per Flight)



SRB TVC HYD VS. ELA (INTERIM RESULTS)

(Cost Savings = $ 2.0M Per Flight)



CONFIRMATION STUDY ON ELA COST SAVINGS APPROVED FOR FY 1992

Future Plans

- Continue updating SRB TVC Life Cycle Costs
- Support New Launch System studies
- Begin identifying Orbiter costs in greater detail
- Establish capability to support operational demonstrations for the investigation of:
  - Safety
  - Ground support equipment (GSE)
  - Facility requirements
  - Operability investigations:
    - Installation
    - Replacement
    - Test and problem isolation
    - Servicing & maintenance
    - Processing flow analysis & resource usage
    - Launch commit criteria and hold impact

NASA Electrical Actuation

Technology Bridging Workshop

ELA Ground Support Applications

at the

John C. Stennis Space Center

W. W. St. Cyr

Technology Development Division
Science & Technology Laboratory

POTENTIAL ELA GROUND APPLICATIONS AT SSC

- Variable position valve of NASP High Heat Flux Test Facility
- Automation of High Pressure Gas Facility
- CTF Test Cell
- Seal Configuration Tester
- Selected Facility Support System Valves

C-6

GOALS OF ELA PROGRAM AT SSC

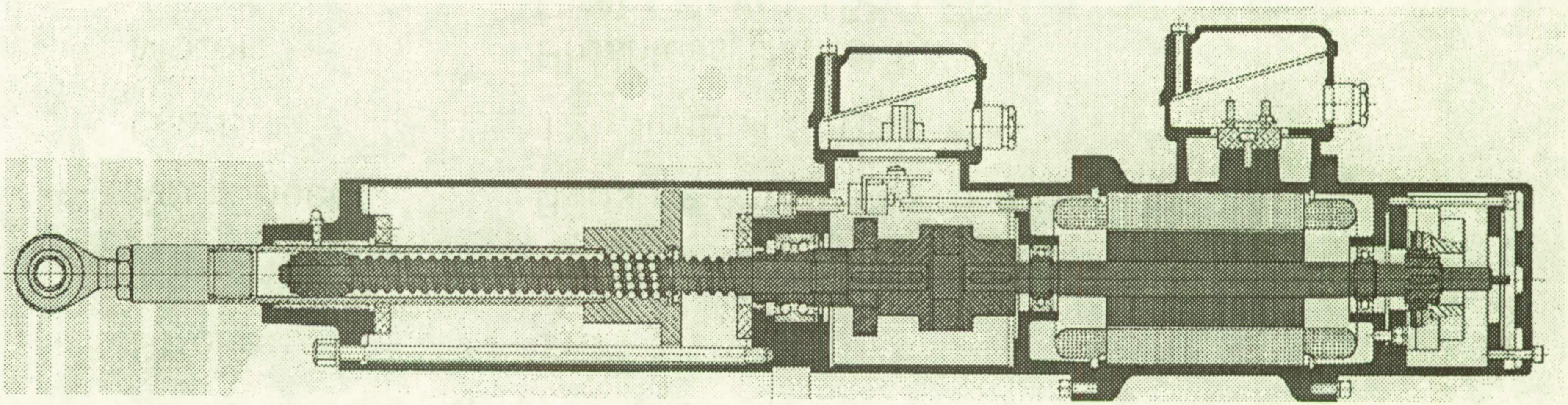
- Determine significant advantages and disadvantages of using ELA's for facility valve actuation.
- Compare operating characteristics of ELA's to those of hydraulic control valves.
- Establish reliability of commercially available ELA hardware when used on facility control valves.
- Determine the compatibility of ELA control interfaces with existing facility data acquisition and control systems.

PROGRESS TO DATE / PROGRAM STATUS

- Requirements have been established for specific applications.
- Identified commercial hardware for ground support applications.
- Developed test plan.
- Electrical Actuator (commercial hardware) in Procurement.
- Adapting test plan to commercial hardware.
- Commercial hardware to be evaluated:
  - ELA hardware to be tested Oct/Nov on Seal Configuration Tester,
  - Field application and evaluation of ELA during 2nd, 3rd and 4th quarter of FY93.

STENNIS SPACE CENTER
ELECTRICAL ACTUATOR ASSESSMENT

RACO INTERNATIONAL



P/1-1/9-25-92

ELA SPECIFICATIONS

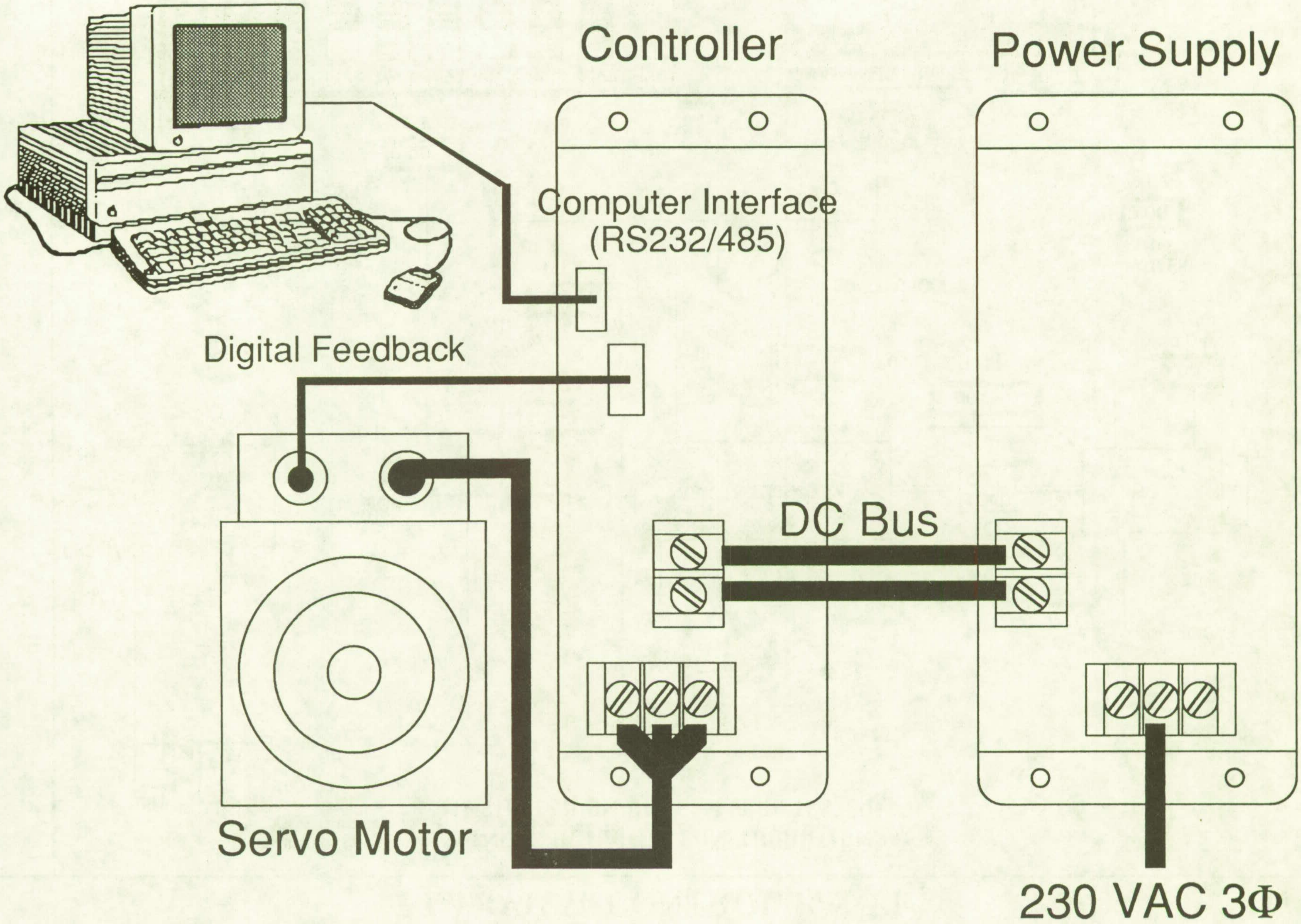
Manufacturer:	Raco International, Bethel Park, PA
Stroke:	7.9"
Thrust:	5000 lbs
Rod Speed:	6 ips peak running (5.5 Hz max)
Lead:	12 mm Ball Screw
Motor:	Brushless Digital Servo Direct Drive, 1550 RPM
Mounting:	Front Flange & Trunnion Brackets
Length:	Approx. 6'
Accessories:	Power Release Brake, Spring loaded front clevis, Stroke limit switches, Rotary encoder for linear displacement

ELA SERVO MOTOR HIGHLIGHTS

- 3 Phase Brushless Servo Motor
- Position Repeatability: Better than one arc-minute
- Maximum Speed: 1550 RPM
- Continuous Torque: 80 lb.ft.
- Rotor Inertia: 0.0093 $lb.ft.sec^2$
- Load Inertia Range: 0 to 0.0465 $lb.ft.sec^2$

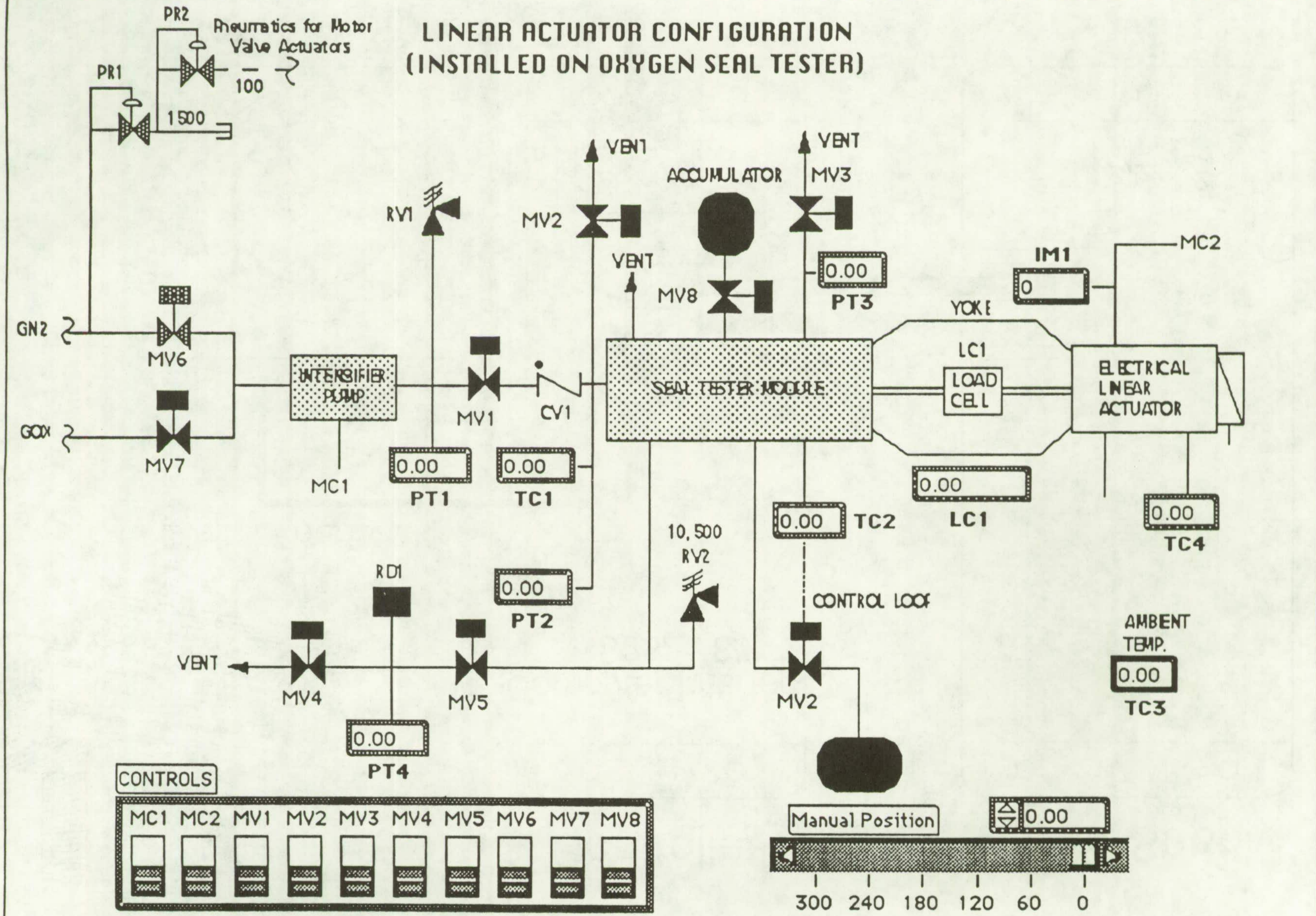
ELA CONTROLLER HIGHLIGHTS

- 10 kHz PMW Switching Frequency
- 55 Amp/Phase Continuous Current
- 110 Amp/Phase Peak Current
- 230 V RMS Nominal Voltage


Controller
Power Supply
Computer Interface
(RS232/485)
Digital Feedback
DC Bus
Servo Motor
230 VAC 3Φ

ELECTRICAL ACTUATOR TESTBED

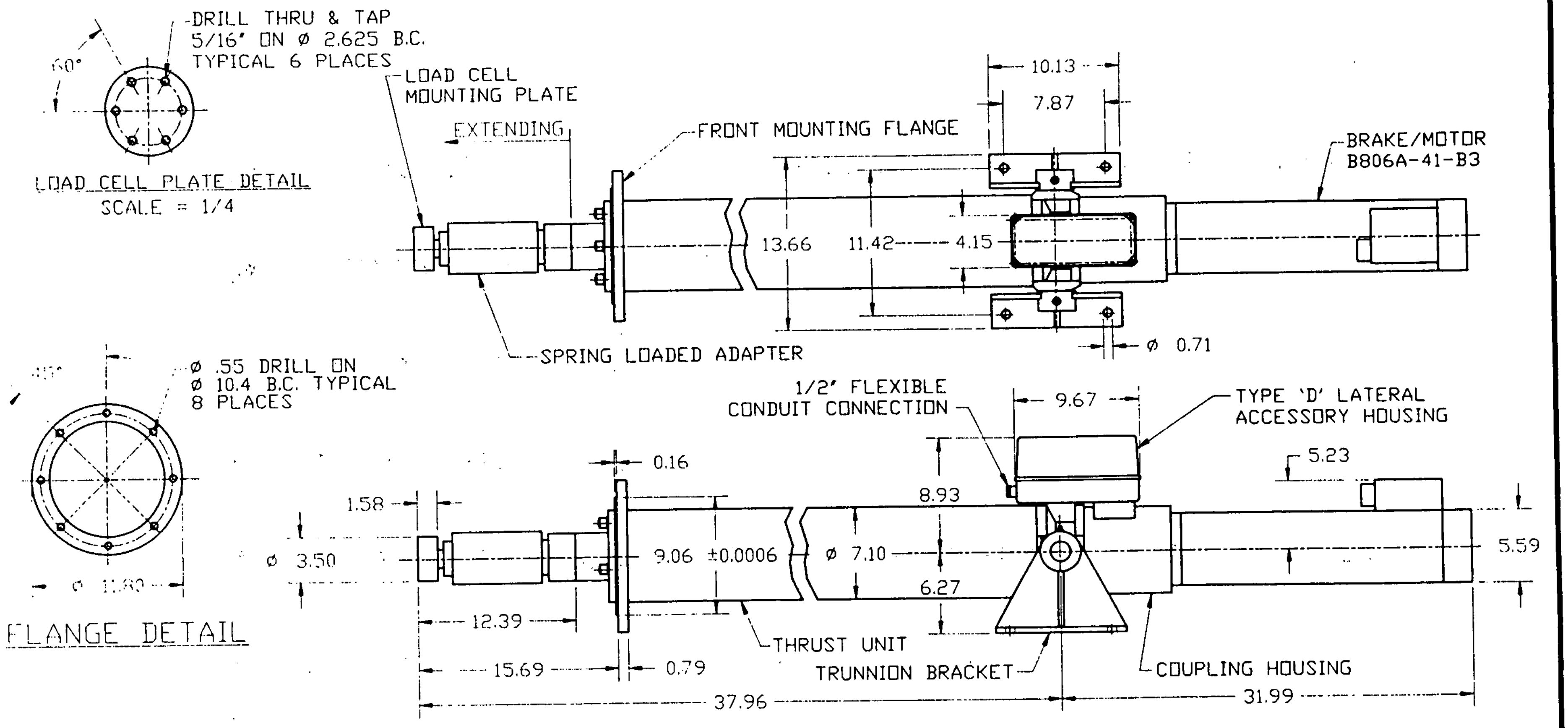
LABVIEW CONTROL PANEL



9/24/92

ELA TESTBED MEASUREMENTS

- Load (10 kHz sampling)
- Linear Position (10 kHz sampling)
- Linear speed and acceleration (derived from position)
- Motor current draw
- Motor temperature
- Total run time
- Wear characteristics of critical ELA drive components

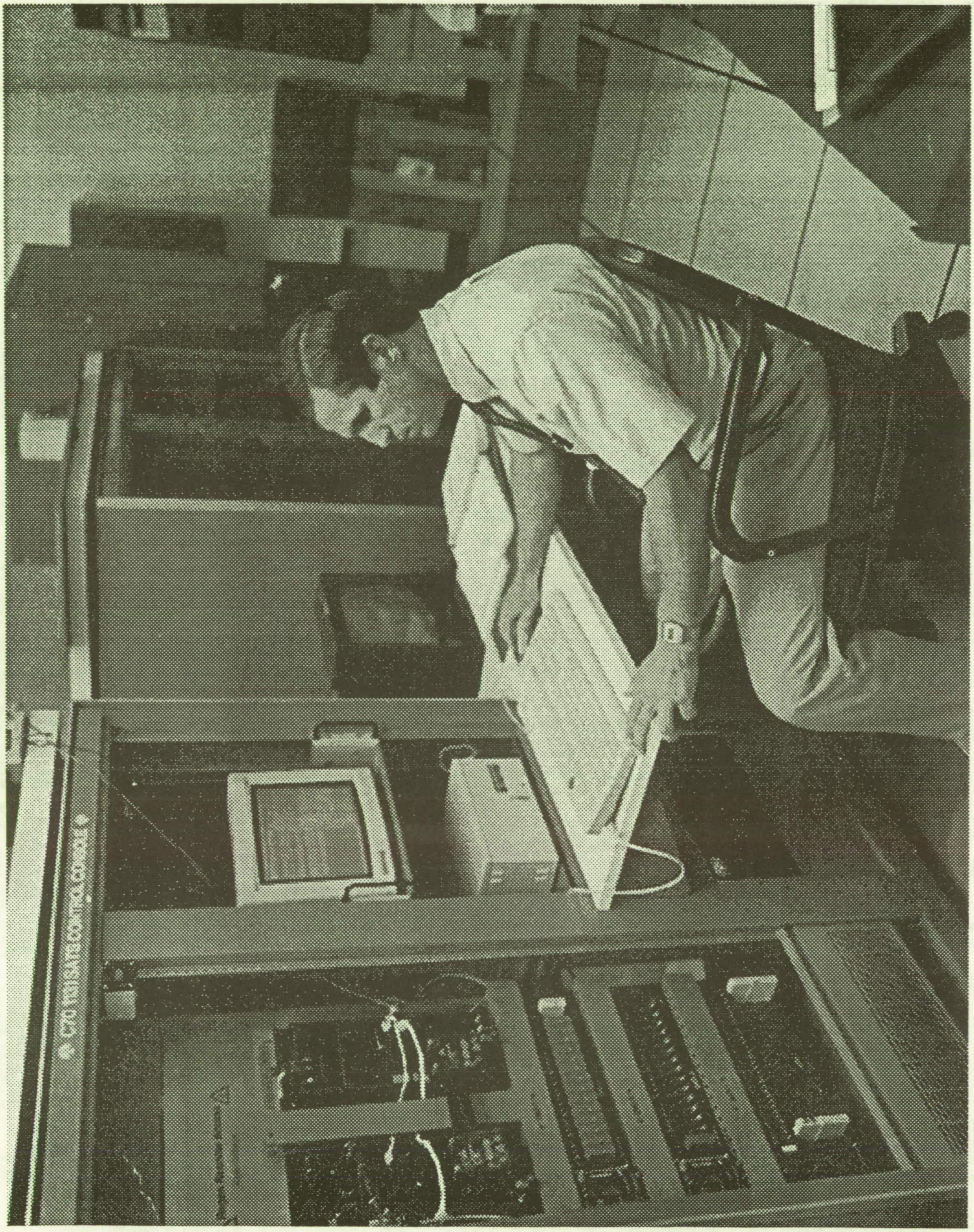


NOTE:

1. ALL DIMENSIONS ARE IN INCHES.
2. ACTUATOR IS SHOWN IN RETRACTED POSITION.
3. THRUST TUBE DIAMETER 2.4"
3. QUOTATION #3879.

REVISIONS			
RACO	RACO INTERNATIONAL, INC. P.O. BOX 151 BETHEL PARK, PA 15102		
TITLE	TYPE F7 ACTUATOR WITH FRONT FLANGE AND TYPE 'D' LATERAL ACCESSORY HOUSING STROKE = 7.9"		
SCALE 1/8	DR. BY P. SPANO	DRAWING NO. GAFZD001	
DATE 6-4-92	CK'D. BY P. SPANO		

ORIGINAL PAGE IS
OF POOR QUALITY



ELA CONTROLLER, POWER SUPPLY, AND OPERATOR CONSOLE

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BLACK AND WHITE PHOTOGRAPH

POWER-BY-WIRE FLIGHT DEMONSTRATIONS ON LASC'S HTTB

Lockheed
High Technology Test Bed
HTTB

9596-15
11-19-92

High Technology Test Bed Program

- Provides a Flying, Operational-Environment Laboratory
- Goals
  - Establish Real-World Mission Characteristics
  - Develop Flight-Tested Hardware
  - Serve as a Focus for Systems Integration
  - Demonstrate Technological Commitment
  - Conduct Applicable Research Projects

9596-26
11-19-92

HTTB Technologies

- Short Takeoff and Landing
- Fly-by-Wire
- Voice I/O
- Infrared
- High Pressure Hydraulics
- High Speed Data Bus
- Fiber Optics
- Autonomous Navigation
- Head-Up Display
- Digital Flight Control

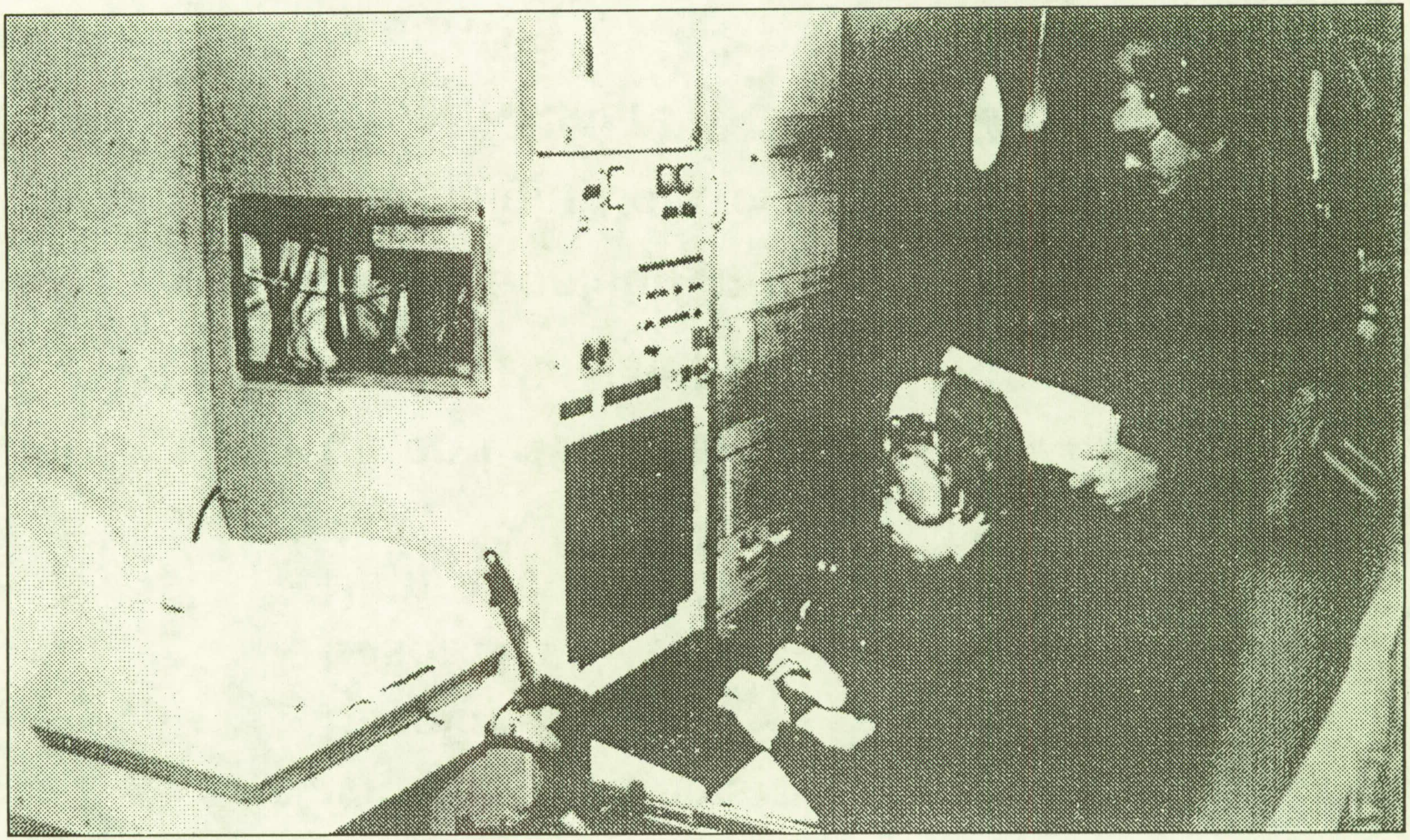
9596-23
11-19-92

Lockheed Airborne Data System (LADS)

- Recording System Installed
- Multiple Measurements Available
- Modular/Expandable
- Real-Time Data
- Processed Output in Engineering Units
- Scan Rates to 160/Sec

9596-25
11-19-92

Lockheed Airborne Data System



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11-19-92
opt 32a

HTTB Advanced Avionics

- Navigation Systems
  - Baseline Delco
  - Laser Nav
  - High Accuracy Gimbal
  - F^3
  - Litton LN92/Collins GPS
- Head Up Display (HUD)
- Forward Looking Infrared (FLIR)
- Digital Flight Control System (DFCS)
- Doppler/Kalman
- Digital ADF
- TACAN

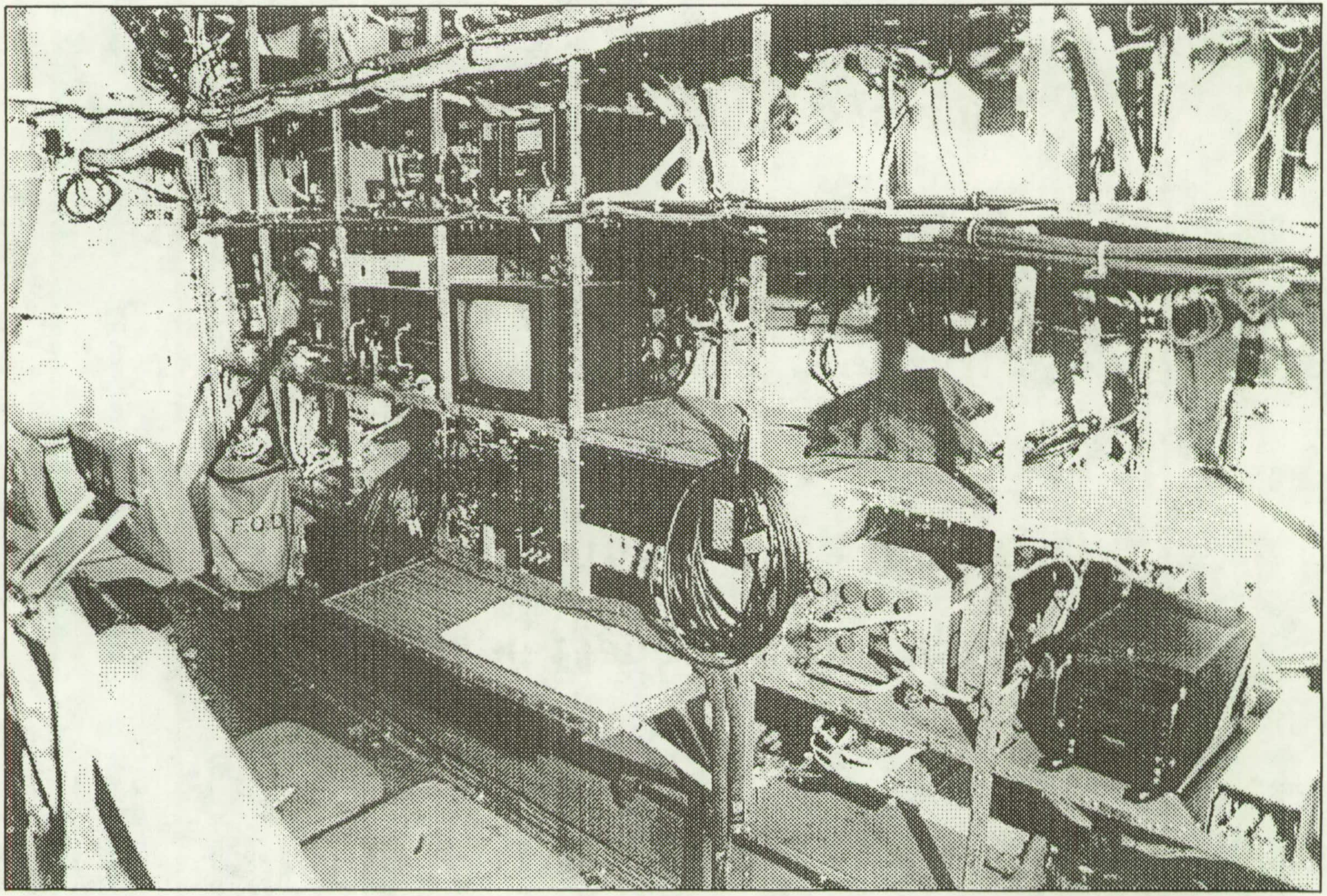
9596-21
11-19-92

HTTB Advanced Avionics

- Cockpit Management System
- MIL-STD-1553B Data Bus
- Radar - Bendix APS-133
  High Resolution Radar
- Radar Altimeter
- Digital Air Data Computer
- Global Positioning System

9596-22
11-19-92

Avionics Bay



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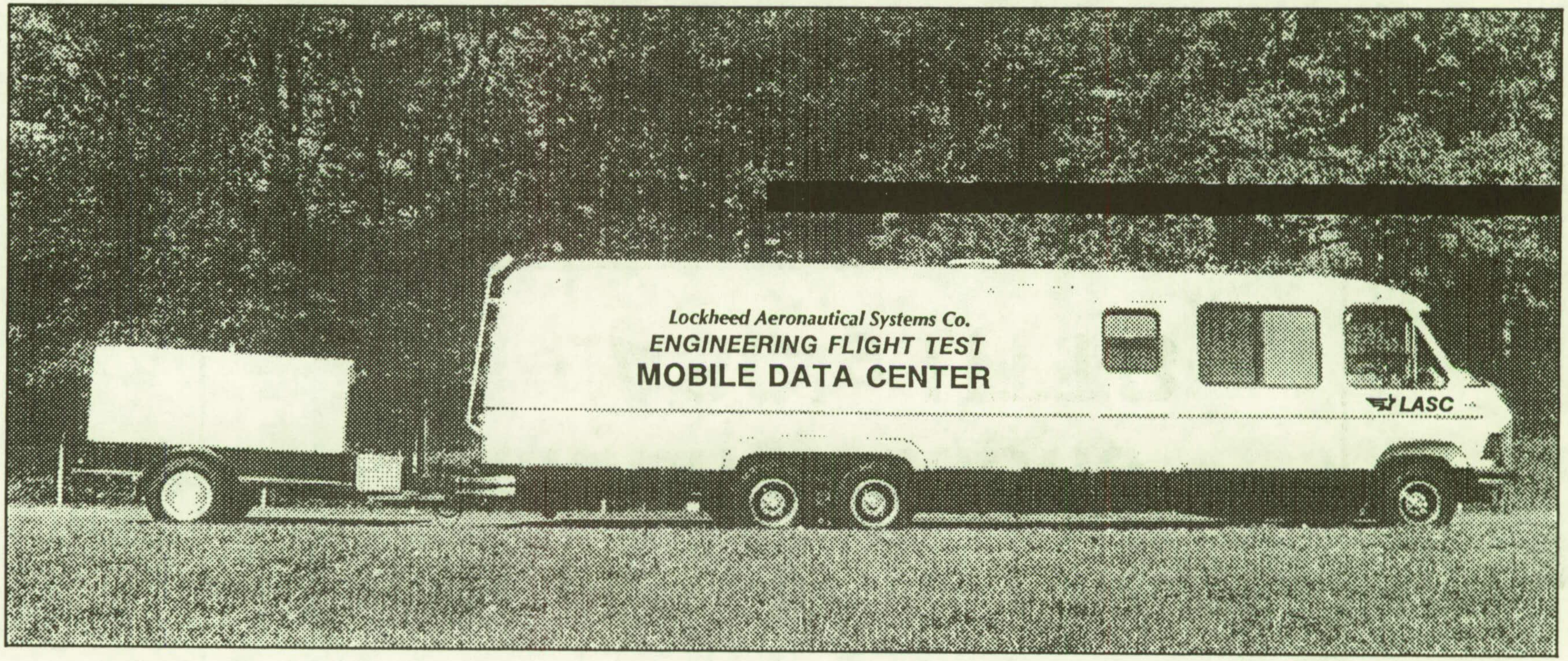
opt 32b

Mobile Data Center



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opt 32b

Power-by-Wire Flight Demonstrations On LASC's HTTB

9596-32
11-19-92

Power-by-Wire Advantages for C-130

- Better Reliability and Supportability
- Damage Tolerance Design (Reduced Vulnerability)
- Jam Resistant
- Energy Efficient (Power "On-Demand")
- Rapid Deployment Capability at Low Temperatures
- Backdrive Capability
- Reduced Fire Risk
- Field Level Hazardous Waste Reduction

9596-20
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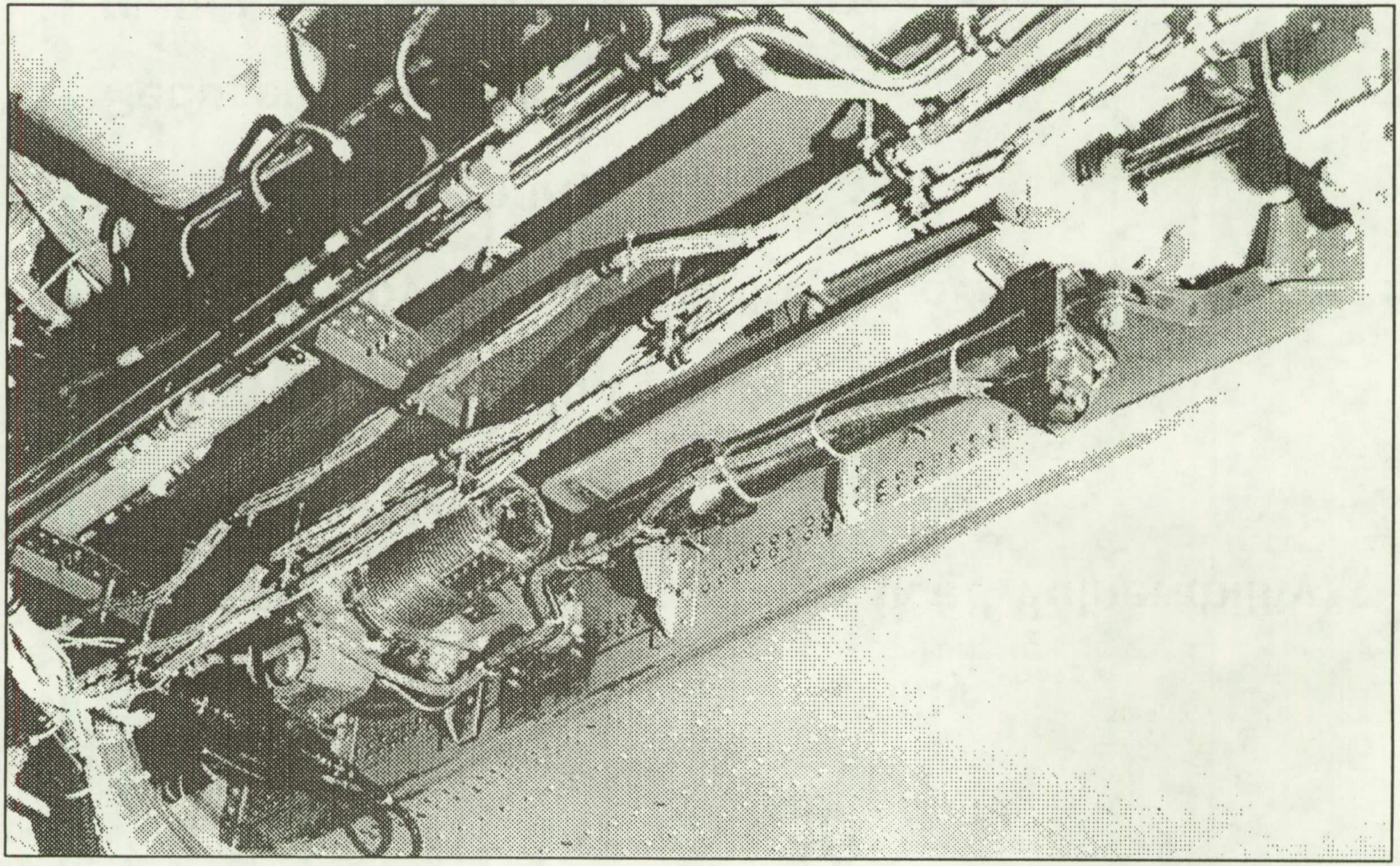
Electro Hydrostatic Actuator - Left Aileron



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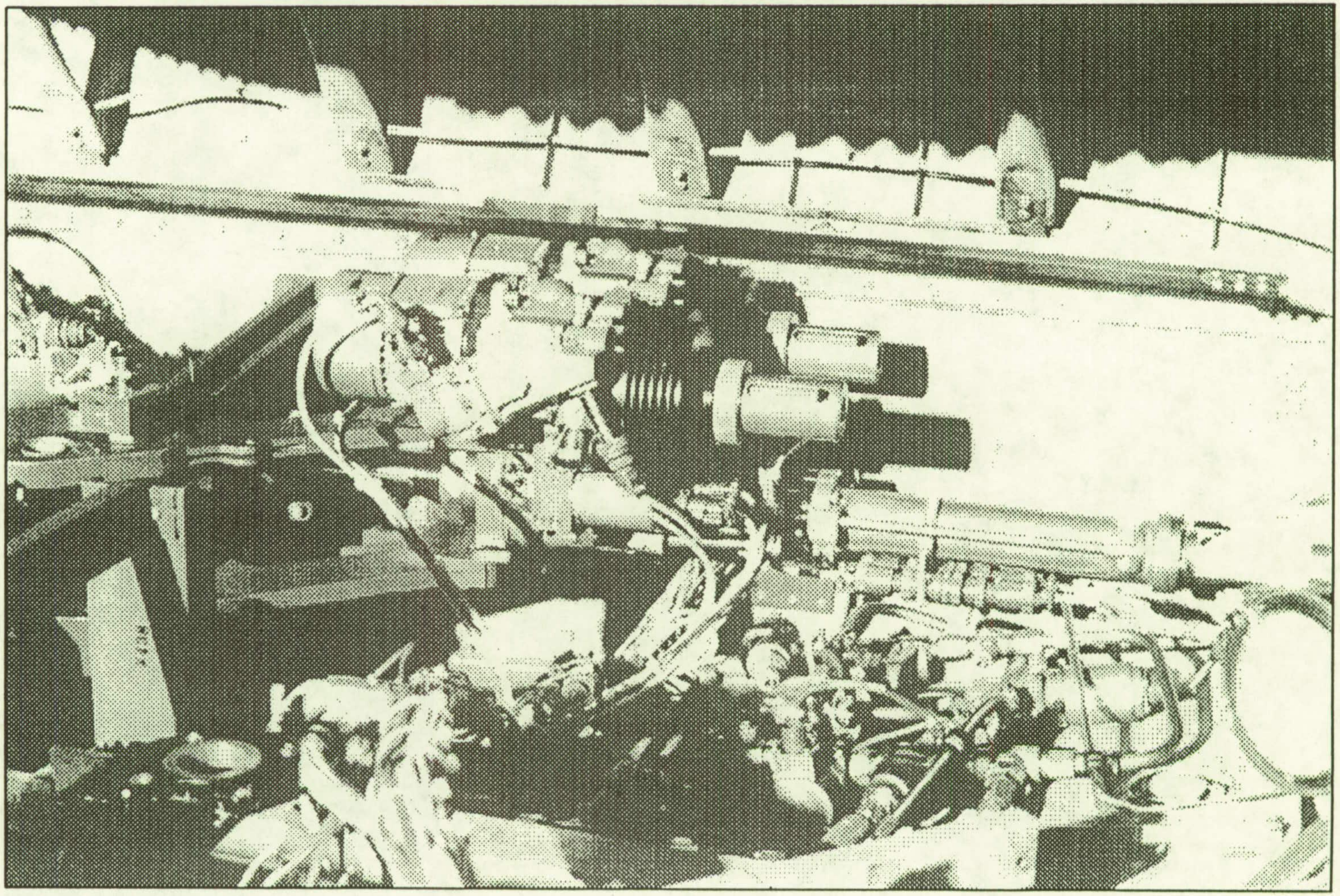
opt 32b

Integrated Actuator Package-Rudder



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opt 32b

SESSION VIII

ELA PROTOTYPE DESIGN AND TEST RESULTS

General Dynamics EMA Testing at NASA MSFC

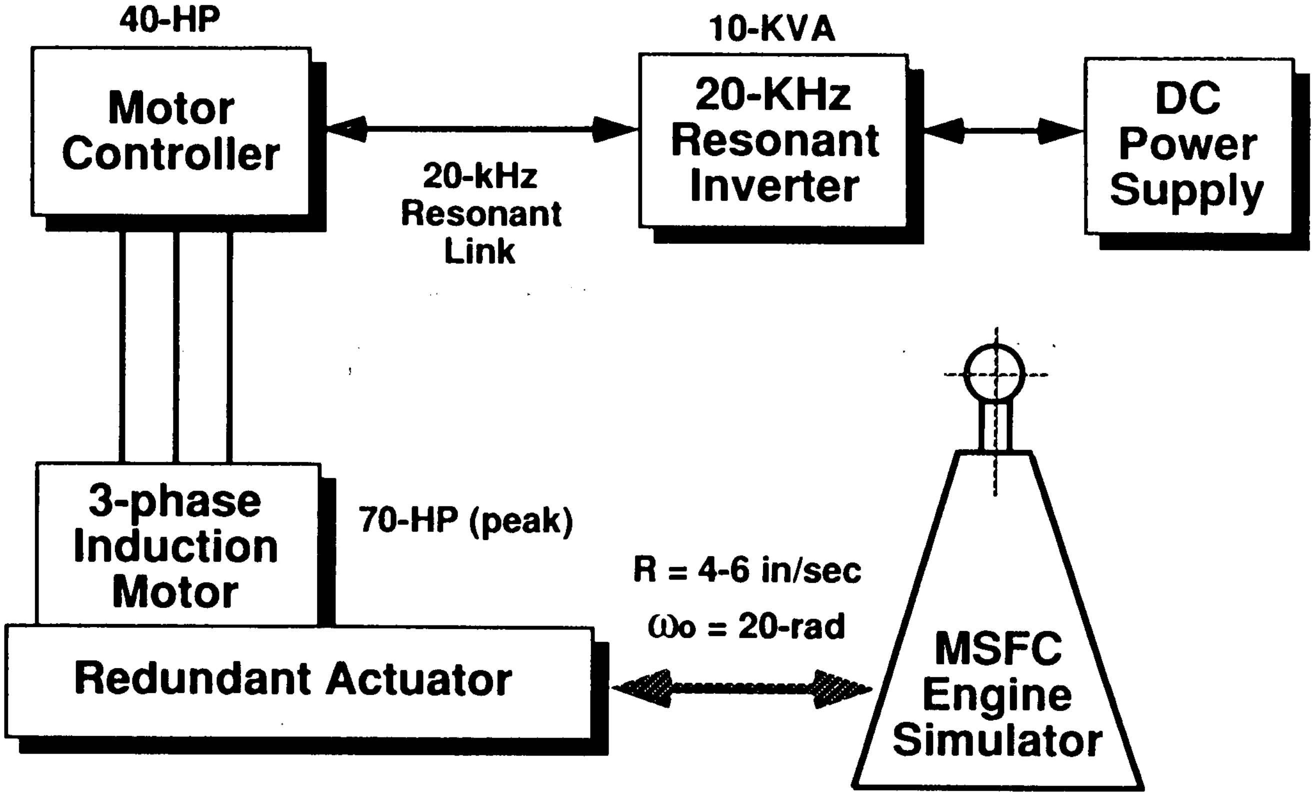
Jim Mildice

General Dynamics
Space Systems Division

October, 1992

General Dynamics EMA Testing at MSFC

Test System Description



General Dynamics EMA Testing at MSFC

Motor Controller Design - *(General Dynamics)*

- **Power Output Stage**
  - Three-phase, bidirectional motor interface
  - High-frequency (20-KHz) AC power input
  - Bilateral output switches, to perform integral, synchronized AC input rectification, and low-frequency motor current synthesis and control
  - Pulse-population regulation, with zero current switching
- **Control**
  - Embedded microprocessor control for all functions except motor current regulation
  - Software in ROM
  - Analog motor current regulation loop, with computer-generated reference
  - All communications and interfaces via serial data busses

General Dynamics EMA Testing at MSFC

Motor Controller Capability

- **Power Inputs**
  - Power Stage Voltage = 300-V,RMS, single-phase, AC
  - Frequency = 20-KHz
  - Total Power = 44.0-KVA (maximum)
- **Command Inputs**
  - Digital, serial data bus - RS-232
- **Feedback**
  - Analog, motor resolver outputs
  - Analog, motor current
- **Outputs**
  - Variable Voltage = zero to 200-V,RMS,L-L; three-phase AC
  - Variable Frequency = zero to 750-Hz
  - Power = 40-KVA (maximum)

General Dynamics EMA Testing at MSFC

Induction Motor - *(Sunstrand)*

- **Electrical Characteristics**
  - Input Voltage = 115-volt,RMS,L-N; three-phase
  - Input Frequency at Full Speed = 750-Hz
  - Power Factor = 0.753
  - Efficiency = 89.9%
- **Mechanical Characteristics**
  - Rated Power = 69.3-HP(peak); 34.6-HP(steady state)
  - Full Rated Speed = 14,700RPM @ Full Load
  - Operating Torque = 148.4 in-lb
  - Maximum Torque = 400 in-lb
  - Specific Weight = 3.32-HP/lb(peak); 1.7-HP/lb(steady state)
  - Specific Volume = 1.6-HP/cu.in(peak); 3.1-HP/cu.in(steady state)
  - Moment of Inertia = 0.0103 in-lb-sec-sec

General Dynamics EMA Testing at MSFC

Redundant Actuator - *(Moog)*

- **Performance**
  - Force Rating = 48,000-lb (operating); 100,000-lb (maximum)
  - Extension = ±5.4-inches
  - Maximum required Rate = 7.4-inches/second
  - Engine Start Transient relief = force feedback with integral load cell
- **Mechanical Design**
  - Design compatible with roller screw or ball screw output
  - Dual (redundant) motor mounts with torque summing in the gear train (no mechanical decoupling)
  - Length = 47.33-inches, pin-to-pin
  - Weight = 300-lb (non-optimized prototype)
  - Moment of Inertia (at the motor shaft) = 0.0089 in-lb-sec-sec

General Dynamics EMA Testing at MSFC

Tests Performed

- **Compatible Operation**
  - Low power test to verify EMA/Controller/Facility compatibility
  - Full power operation to verify EMA/Controller/Facility compatibility
- **Step Response**
  - Step function position commands from (+) to (-) 0.05- to 2.5-inches
  - Maximum rate achieved ≈ 6-inches/second (consistent with input power limitation)
- **Frequency Response for various displacements**
  - Combinations of frequencies and displacements from 0.1-Hz @ ±0.05-inch to 4.0-Hz @ ±0.25 inch
  - Small signal bandwidth ≈ 20-radians
  - Typical power (slew rate) limited frequency response ≈ 2.0-Hz @ ±0.5-inches

General Dynamics EMA Testing at MSFC

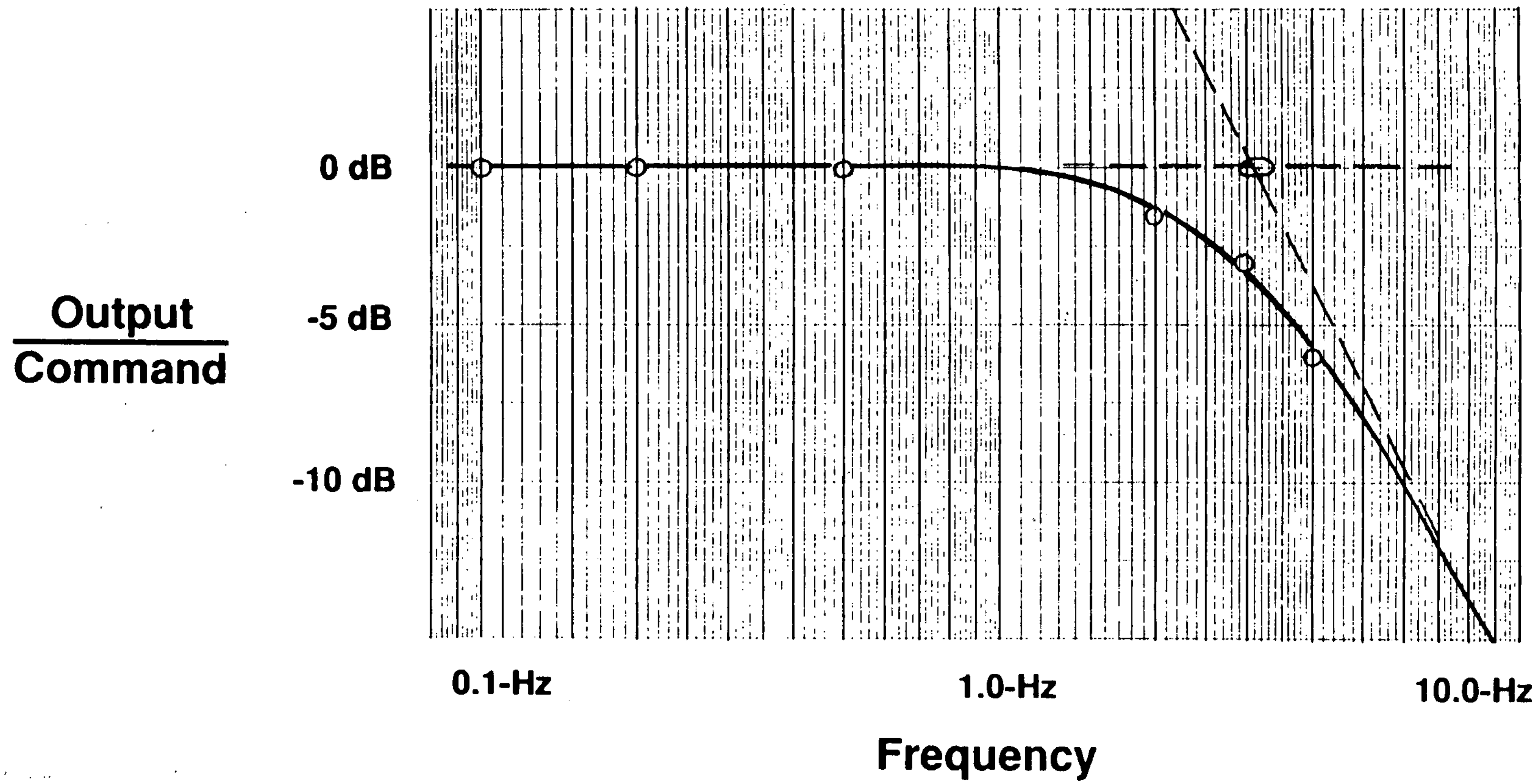
Special Conditions and Limits

(for This Test Only)

- **Engine position control loop software/system response designed to NLS-2 requirements**
  - Position control loop bandwidth limited to 20-radians
- **High-frequency AC controller input power limited to 10-KVA by the inverter capability**
  - Step response limited to approximately 6-inches/second
  - Large signal frequency response is slew-rate limited. Limiting typically starts at about 2.0-Hz @ ±0.5-inches

General Dynamics EMA Testing at MSFC

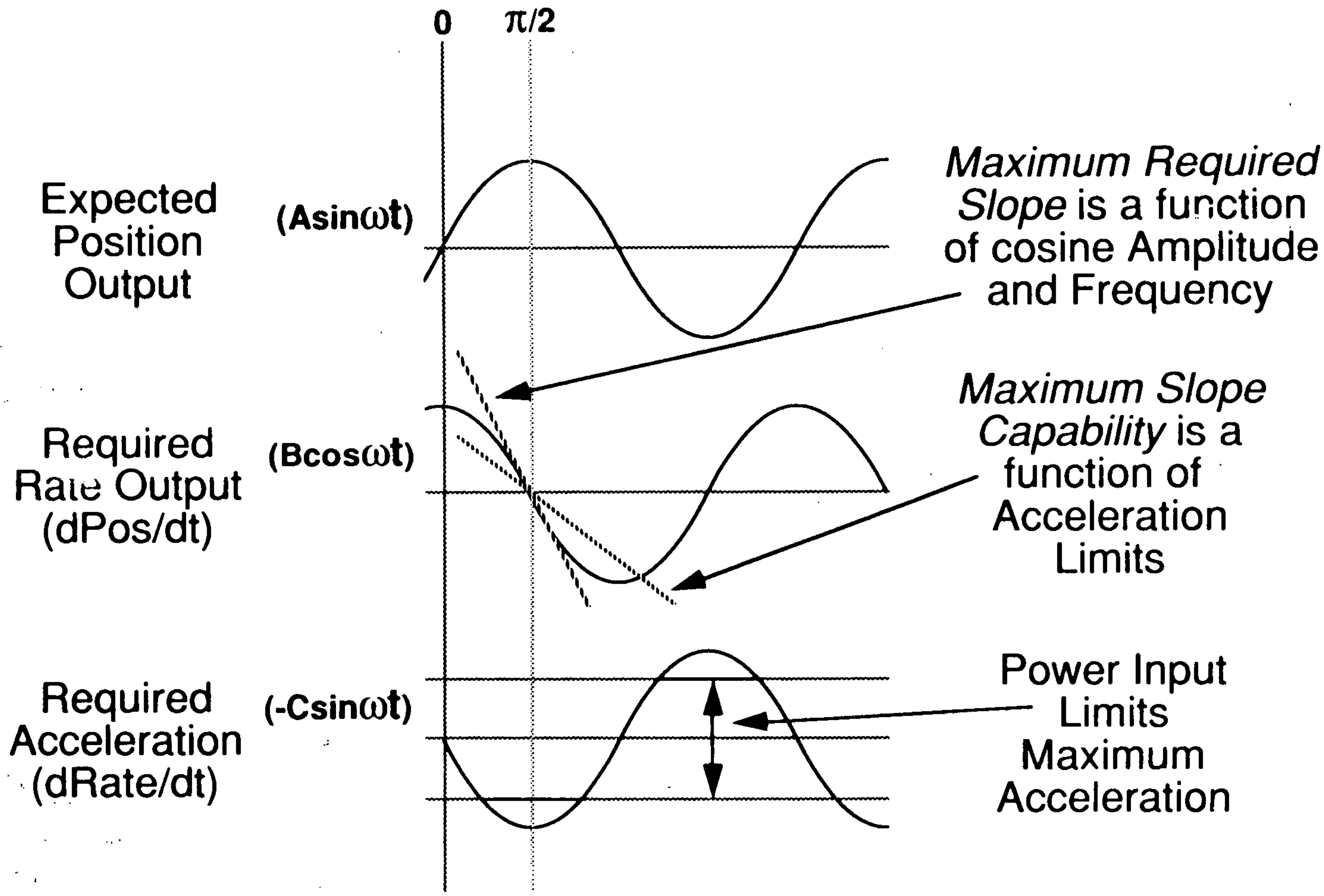
Small Signal Frequency Response



Data is consistent with the design for a critically-damped, second-order system with a 20-radian (3.2-Hz) bandwidth

General Dynamics EMA Testing at MSFC

Frequency Response Limit



Frequency Response

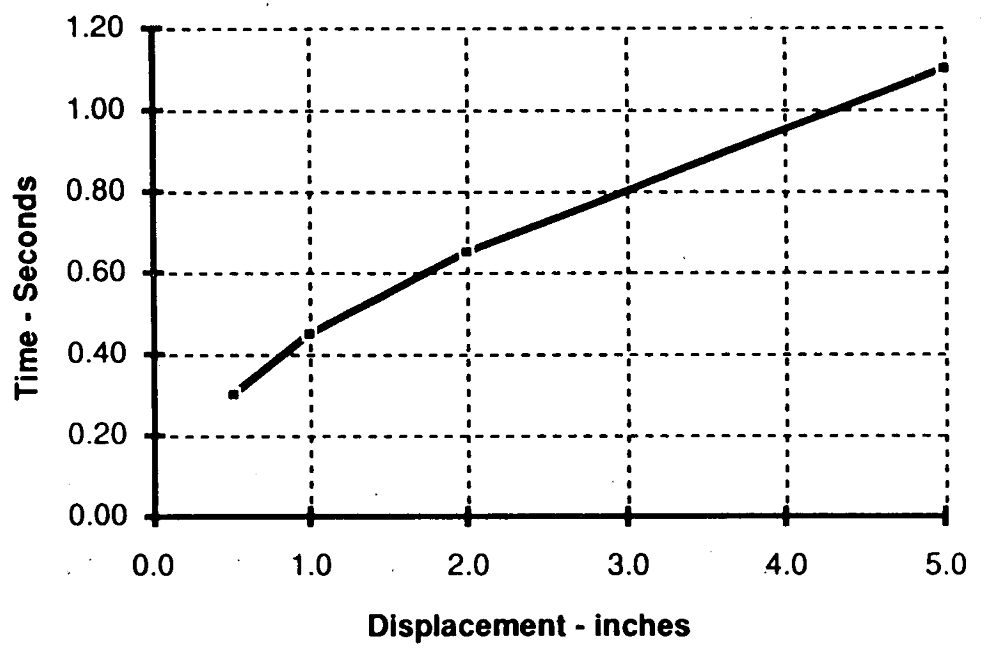
- **Limited input power limits the torque available for acceleration**
  - $\text{Torque}_{(accel)} = \text{Torque}_{(total)} - \text{Torque}_{(load+friction)}$
- **At the limit, acceleration is constant, the maximum rate change slope is constant, and the system becomes "slew rate" limited**
- **The constant value rate change slope, for a "slew rate" limited system *(Maximum Slope Capability)* must be larger than the *Maximum Required Slope* for the rate output**
  - If it is not, the output amplitude is limited

- **After we work through the math, Slew Rate limit for frequency response is:**

$$f_{SR} \leq \frac{SR}{(2\pi \times B_{pk})}$$

General Dynamics EMA Testing at MSFC

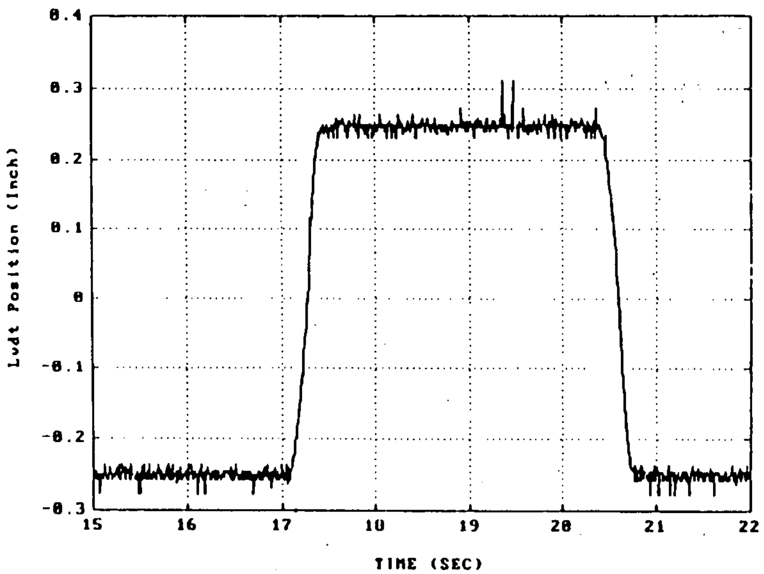
Step Response Average Rates



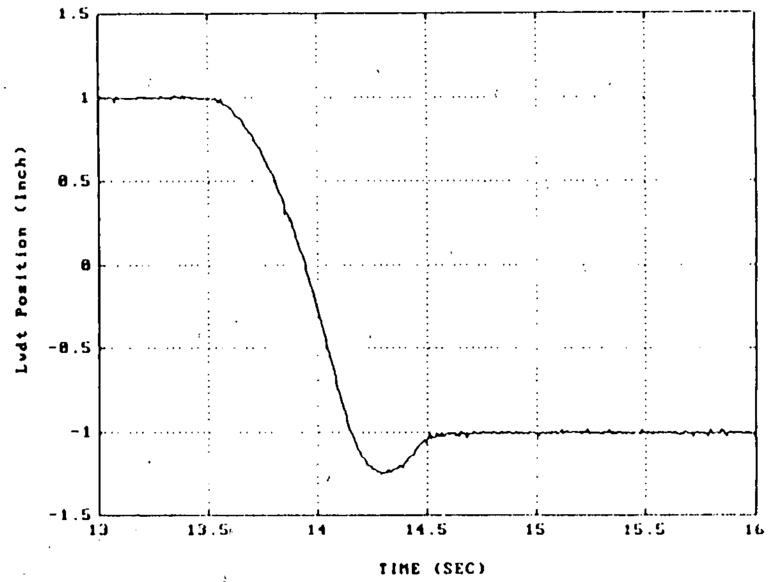
Step Response is consistent with power limits

General Dynamics EMA Testing at MSFC

Step Response Typical Characteristic



Step = 0.5-inches
Max Rate = 4.5-in/sec
(no power limiting)



Step = 2.0-inches
Max Power-limited
rate = 6.0-in/sec

General Dynamics EMA Testing at MSFC

Summary

- **General Dynamics EMA testing at MSFC was satisfactorily completed during the week of September 8-11**
- **Evaluated test results were within expected ranges**
  - Small-signal bandwidth ≈ 20-radians
  - Power-limited maximum rate ≈ 6.0-inches/second
  - Accuracy & Linearity are better than the resolution of the data
- **Maximum potential capability was not demonstrated due to the following:**
  - Control system bandwidth was designed to meet the NLS-2 requirement of 20-radians
  - Motor controller power input was limited by the capability of the source, which resulted in a limited large-signal amplitude-bandwidth

Design of A High Power Prototype Electromechanical Actuator For Thrust Vector Control

Rusty Cowan

NASA

George C. Marshall Space Flight Center

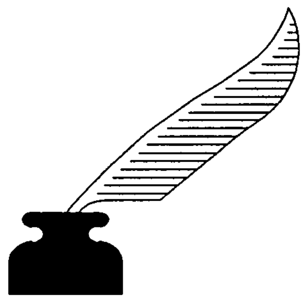
NASA ELA-TB Workshop

September 29 - October 1, 1992

AGENDA

EMTVC Actuator

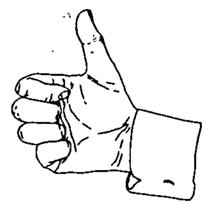
- Introduction - Why EMA?
- Design - EMTVC Actuator
    - Baseline Parameters
    - Major Components



- Testing
- EMTVC Actuator Program Development
- Conclusions

WHY ELECTROMECHANICAL ?

- HYDRAULIC SYSTEM INSPECTION TIME
  - ORBITER ON BOARD HYDRAULIC COMPONENTS-APPROX 300
  - ORBITER GROUND SUPPORT COMPONENTS-APPROX 140
- CLEANER, LESS CUMBERSOME
- PROVIDES ALTERNATE TVC SYSTEM
- LOW MAINTENANCE
- PROVEN TECHNOLOGY



- HISTORICAL HYDRAULIC HEADACHES
  - EXCESSIVE MAINTENANCE AND GROUND SUPPORT (INCREASES COST AND MAN-HOURS)
  - FLUID CONTAMINATION (FILTERING)

DESIGN

MSFC
EMTVC Actuator

PROPULSION LABORATORY
EP64 Branch

BASELINE REQUIREMENTS

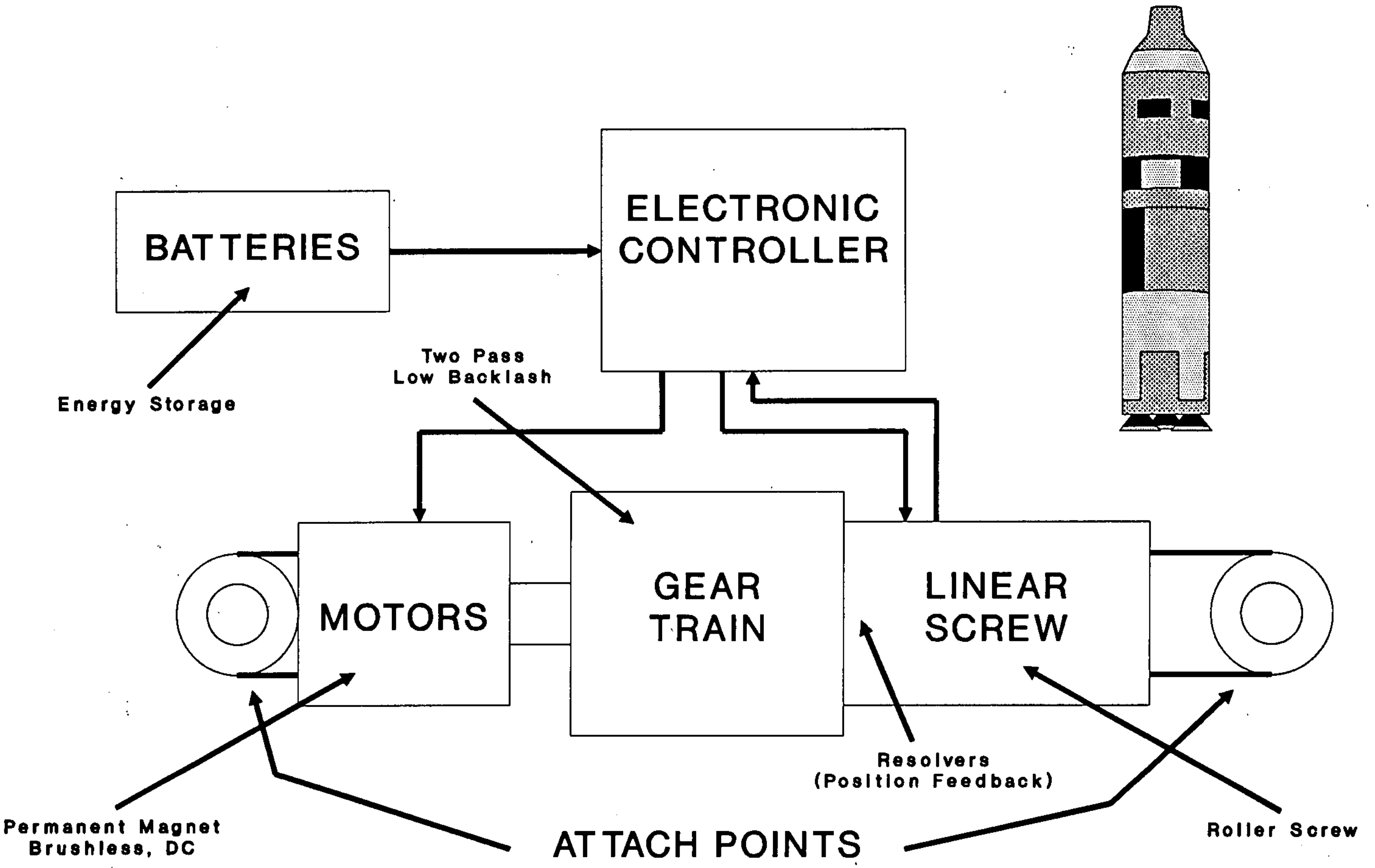
SRM, SSME, NLS CLASS

- PROTOTYPE PHILOSOPHY
  - LOW COST
  - QUICK TURNAROUND
  - LEARN FROM EXPERIENCE

- ESTABLISHED PARAMETERS (SRM, SSME, NLS CLASS)
  - RATED DYNAMIC CAPACITY OF 35KLB
  - MAXIMUM STROKE OF +/-6.00 IN
  - RATED VELOCITY OF 5 IN/SEC
  - CONTROL - TWO CHANNEL REDUNDANT (FAIL/OP REDUNDANCY)
  - POSITION ACCURACY - $<$ 0.050 IN

EMTVC ACTUATOR

MAJOR COMPONENTS/SCHEMATIC DIAGRAM



LINEAR SCREW

ROLLER/BALL SCREW COMPARISON

- ROLLER SCREW
  - ABILITY TO HANDLE TRANSIENT LOADS
  - HIGHER LOAD CAPACITY
  - SLEEK NUT DESIGN (No Recirculation Channel)
  - SKF SP/PR 48/10
    - 1.89 DIA. SHAFT
    - 0.4 IN. LEAD
    - RATED LOAD OF 40095 LB

GEAR TRAIN

- SPUR, 20 DEG INVOLUTE
- CALCULATED TORQUES
  - OUTPUT = 2228 IN-LB
  - INTERMEDIATE = 303.9 IN-LB
  - INPUT = 243.1 IN-LB
- REQUIRED OUTPUT RPM TO MAINTAIN VELOCITY OF 5 IN/SEC, RPM = 761
- HORSEPOWER REQUIRED = 26.9
- MATERIAL - 8620 Steel Alloy (Case Hardening Qualities)
- GEAR REDUCTIONS (8.75:1 Total)
  - 1ST GEAR PASS, 1.25:1, 7000-5600 RPM
  - 2ND GEAR PASS, 7.00:1, 5600-800 RPM

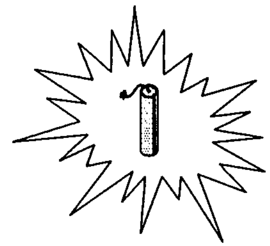
MOTORS

THREE-PHASE, PERMANENT MAGNET, BRUSHLESS, DC

- BASIC CHARACTERISTICS:
  - NO LOAD SPEED: 9300 RPM @ 270v
  - 5.5 in. O.D. x 5.045 in. L
  - WEIGHT: 17 lb
  - OFF-THE-SHELF
- EASILY CONTROLLED - KNOWN DESIGN
- HIGH EFFICIENCY
- BROAD SPEED RANGE
- HIGH TORQUE/WEIGHT/EFFICIENCY
- GOOD THERMAL PROPERTIES
- LARGE # OF POLES
  (NOMINAL DRAG TORQUE IN REDUNDANT SYSTEM)

TESTING

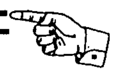
EMA

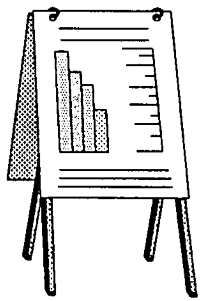


- DYNAMIC TESTS
  - LINEARITY, GAIN, HYSTERESIS
  - FREQUENCY RESPONSE (OUTPUT/INPUT)
  - PISTON VELOCITY
  - STEP RESPONSE WITH INERTIAL LOAD APPLIED
- REDUNDANCY MANAGEMENT CONFIGURATION
- DYNAMIC LOAD SIMULATOR - MSFC, HUNTSVILLE, Al.

EMA DEVELOPMENT

GOALS

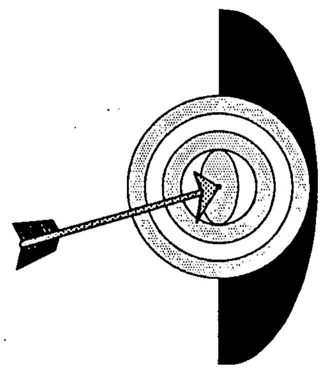
- 60HP QUAD EMA - NEXT GENERATION
  - NLS Prototype Subsystem
  - FAIL/OP, FAIL/OP, FAIL/SAFE
- 30HP (500K LB-1500K LB THRUST VEHICLE)
  - ASRM
  - SSME 
  - NLS
- 10HP (J-II CLASS, 200K LB THRUST)
  - LUNAR MARS TRANSPORT
- 1HP (RL-10 CLASS, 20K LB THRUST)
  - LUNAR MARS LANDER



CONCLUSIONS

EMA

- LESSONS LEARNED
  - GEAR TRAIN (BACKLASH, MANUFACTURING)
  - MOTOR (SHAFTS)
- FEASIBILITY ?
  - DATA LOOKS GOOD ! (John Sharkey)
- DEVELOP DEFINITION & SPECIFICATIONS FOR TVC EM CONTROL SYSTEM
  - LAB SIMULATION TEST
  - VALIDATION TEST (ENGINE HOT FIRE)
- THINGS TO CONSIDER
  - SYSTEM WEIGHT
  - POWER SOURCE
  - MAINTENANCE
  - COST



MSFC IN-HOUSE ACTUATOR TEST RESULTS

John P. Sharkey / Rae Ann Weir
EP64
205-544-7146

SYSTEM DESIGN SPECIFICATIONS

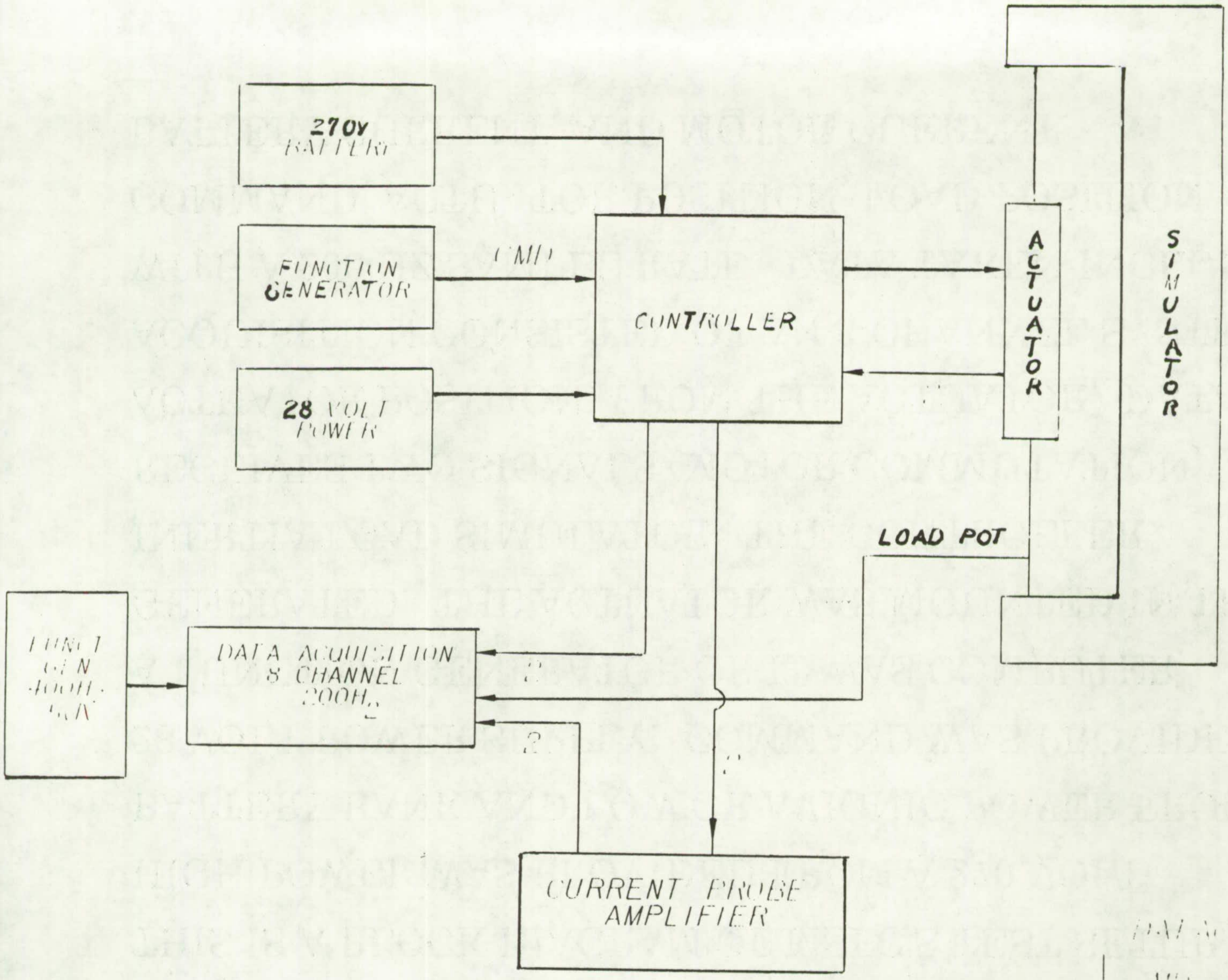
- 3 Hz. Bandwidth (2 to 5% of full stroke)
- Less than 25 degrees of Phase Lag at 1 Hz.
- .050 in. accuracy
- Rate of 5 in/sec.
- Less than 20% overshoot
- Load of 35,000 lbs.

A MSFC TEST PLAN WAS WRITTEN TO COMPLY WITH THE ELA ROCKWELL DEVELOPED ACTUATOR TEST PLAN. DUE TO A FAILURE OF THE LOAD-VS-RATE TEST BED, THE LAST TWO TESTS WERE NOT PERFORMED. UPON MODIFICATION OF THE TEST BED, THESE TESTS WILL BE RUN AND THE RESULTS DOCUMENTED.

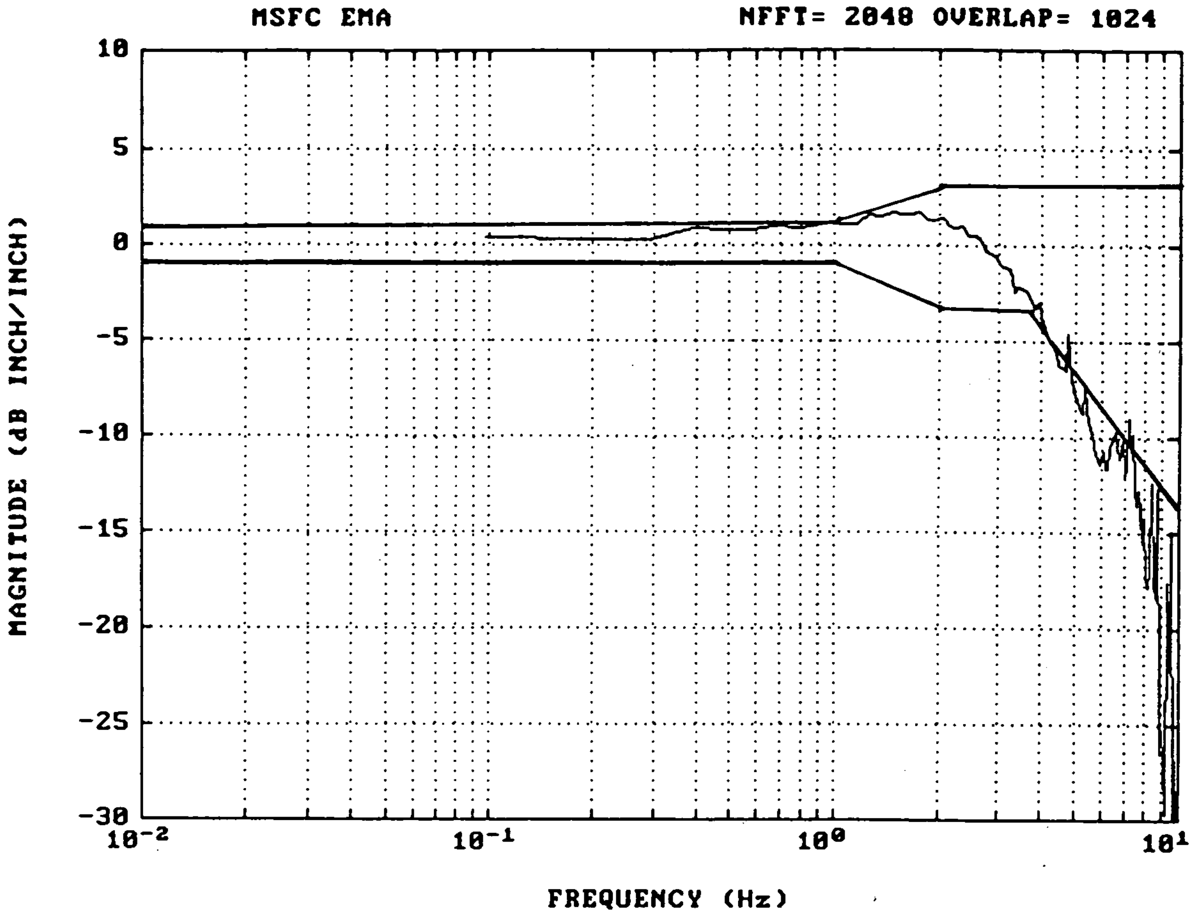
MSFC TVC ACTUATOR TEST PLAN

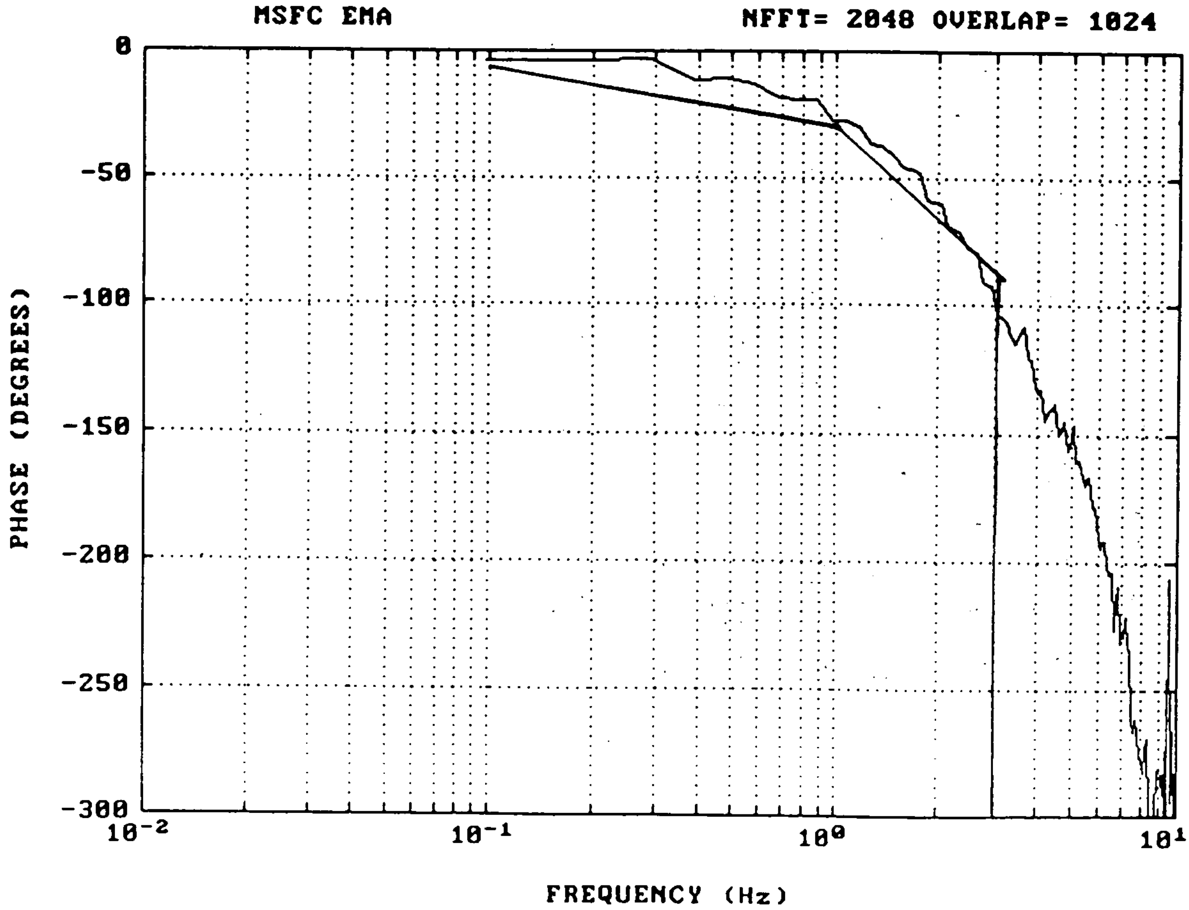
- Frequency Response Tests
- Linearity/Hysteresis Tests
- Step Response Tests
- Rate -vs- Load Tests
- Backdrive and Breakaway Friction Tests

THIS IS A BLOCK DIAGRAM OF MSFC'S TEST SETUP. HIGH POWER WAS PROVIDED FROM A 270 VOLT BATTERY BANK AND LOW OR AVIONIC POWER FROM A 28 VOLT POWER SUPPLY. COMMAND WAS PROVIDED BY A FUNCTION GENERATOR OR IT WAS COMPUTER GENERATED. THE ACTUATOR WAS MOUNTED IN THE INERTIA LOAD SIMULATOR. THE CONTROLLER RECEIVES TWO SIGNALS (MOTOR COMMUTATION, ACTUATOR POSITION) FROM THE ACTUATOR. DATA ACQUISITION CONSISTED OF AN 8-CHANNEL SYSTEM WITH A 200 HZ SAMPLE RATE. DATA TAKEN INCLUDED COMMAND, ACTUATOR POSITION, LOAD POSITION, BATTERY CURRENT, AND MOTOR CURRENT.

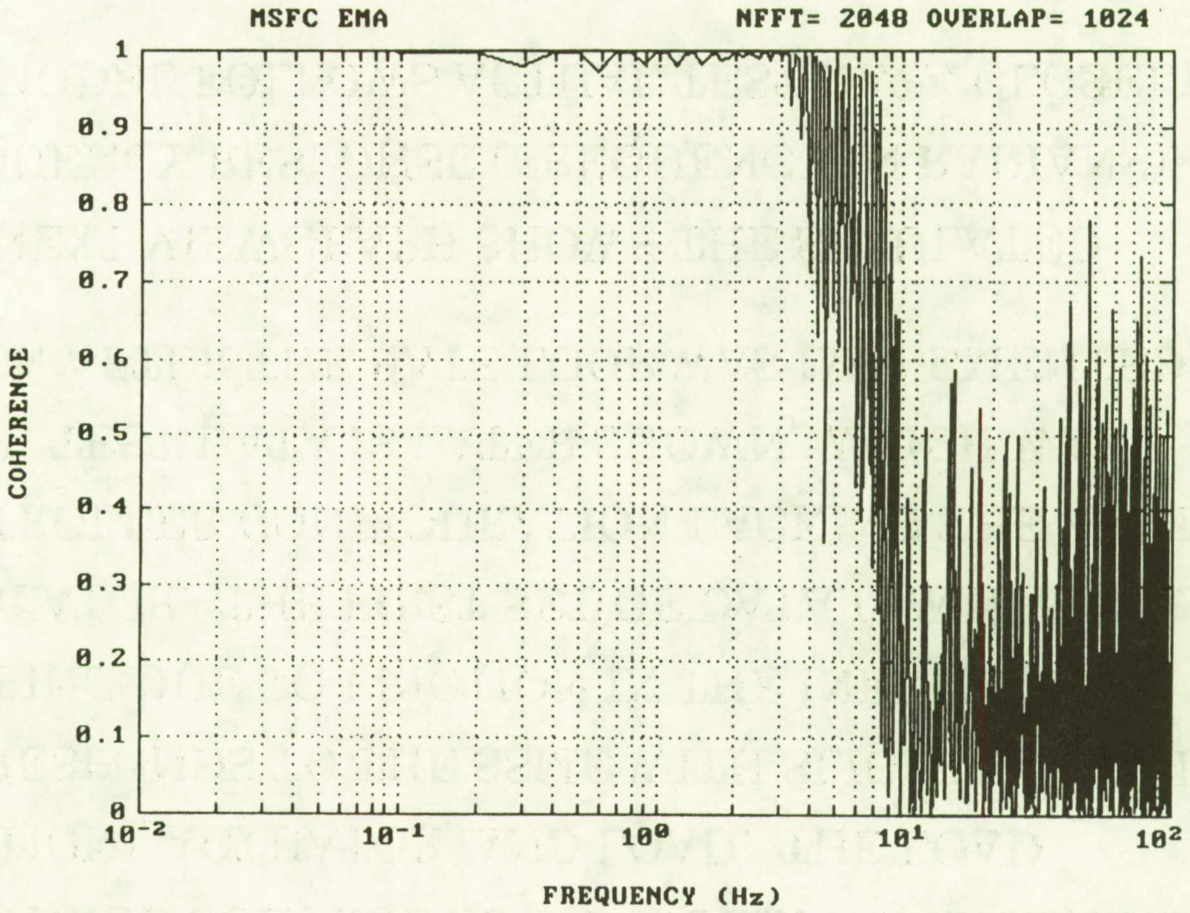

270V BATTERY
FUNCTION GENERATOR
CMD
28 VOLT POWER
CONTROLLER
ACTUATOR
SIMULATOR
LOAD POT
DATA ACQUISITION 8 CHANNEL 200Hz
CURRENT PROBE AMPLIFIER

THE ENVELOPE ON THE FREQUENCY RESPONSE CHART IS THE SSME SMALL SIGNAL REQUIREMENT. DATA SHOWS THE RESPONSE MEETS SSME SPECIFICATIONS. DATA ABOVE 4 OR 5 HZ HAS STARTED LOSING COHERENCE, AS CAN BE SEEN IN THE NEXT CHART. THE BANDWIDTH OF THE SYSTEM IS APPROXIMATELY 4 HZ. THE RESPONSE ALSO MEETS THE > -25 DEGREES OF PHASE LAG AT 1 HZ REQUIREMENT.





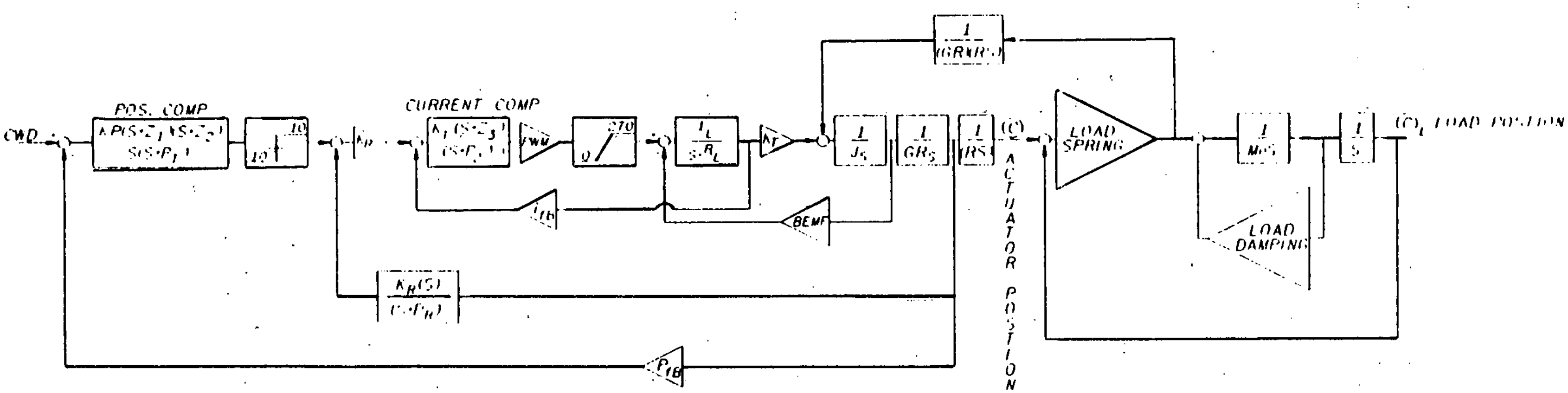
Frequency Response with SSME Envelope Requirements



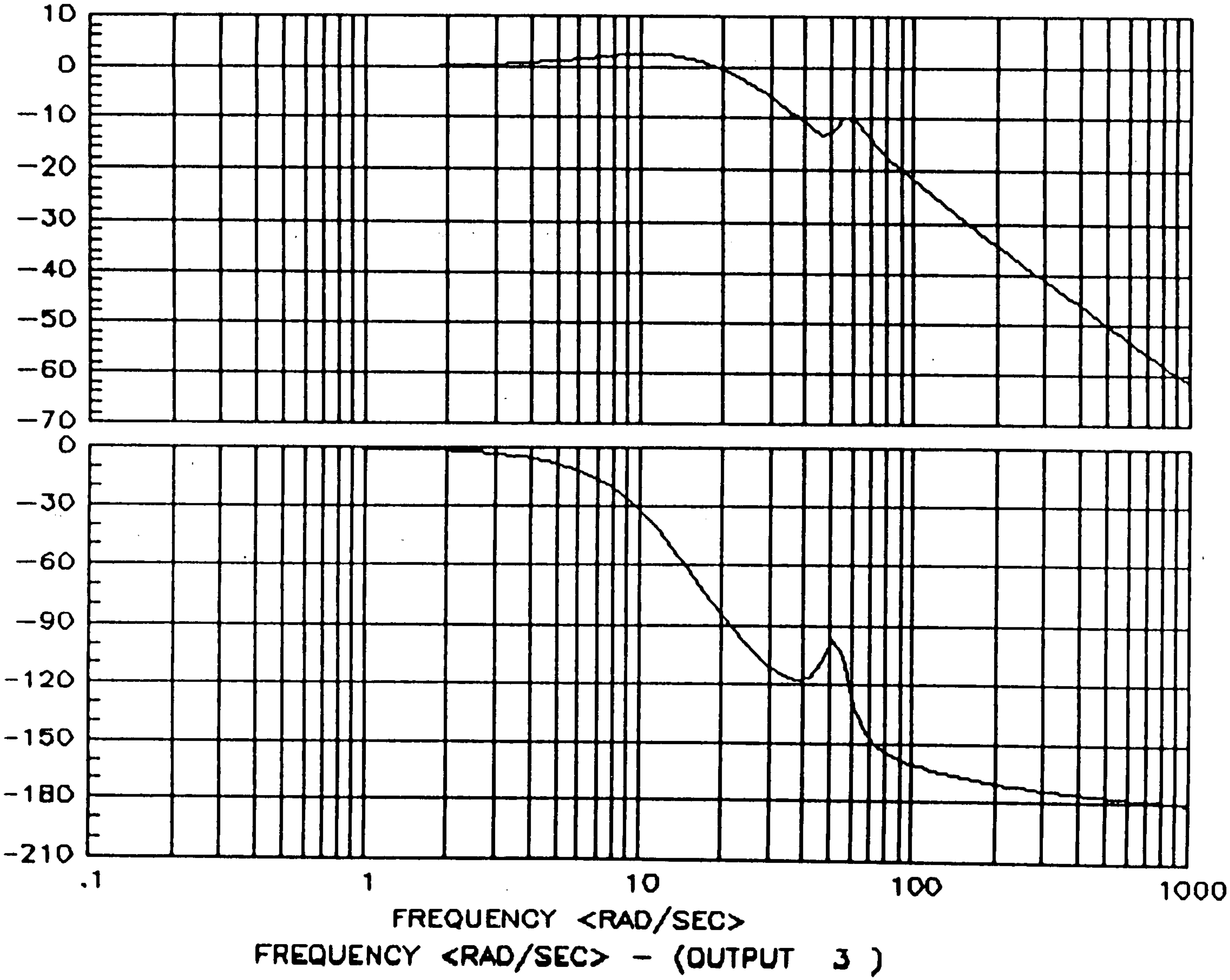
Frequency Response Coherence

THE BASIC CONTROL SYSTEM BLOCK DIAGRAM SHOWS THE THREE CONTROL LOOPS (CURRENT, RATE, AND POSITION), ACTUATOR, AND LOAD. THE LOAD CORRESPONDS TO THE SSME WITH SLIGHTLY MORE DAMPING DUE TO FRICTION IN THE INERTIA LOAD SIMULATOR. THE FIRST SET OF DATA IS WITH A CONTROLLER CONFIGURATION LACKING THE RATE LOOP. TEST DATA IS LATER SHOWN, WHICH WAS TAKEN AFTER THE RATE LOOP WAS IMPLEMENTED.

THE NEXT VIEWGRAPH SHOWS THE SIMULATED FREQUENCY RESPONSE (FREQUENCY IN RADIANS). THE MODEL FOLLOWS ACTUAL TEST DATA CLOSELY.

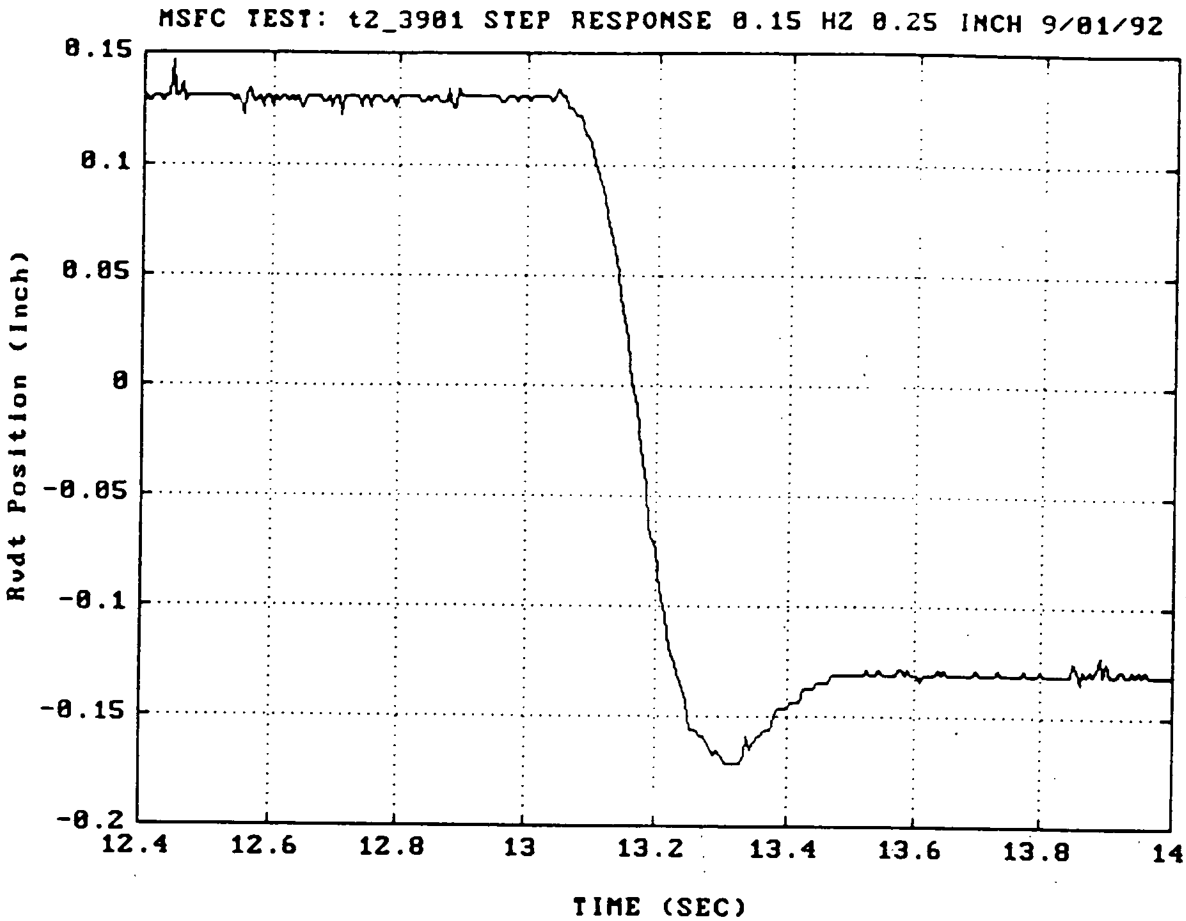


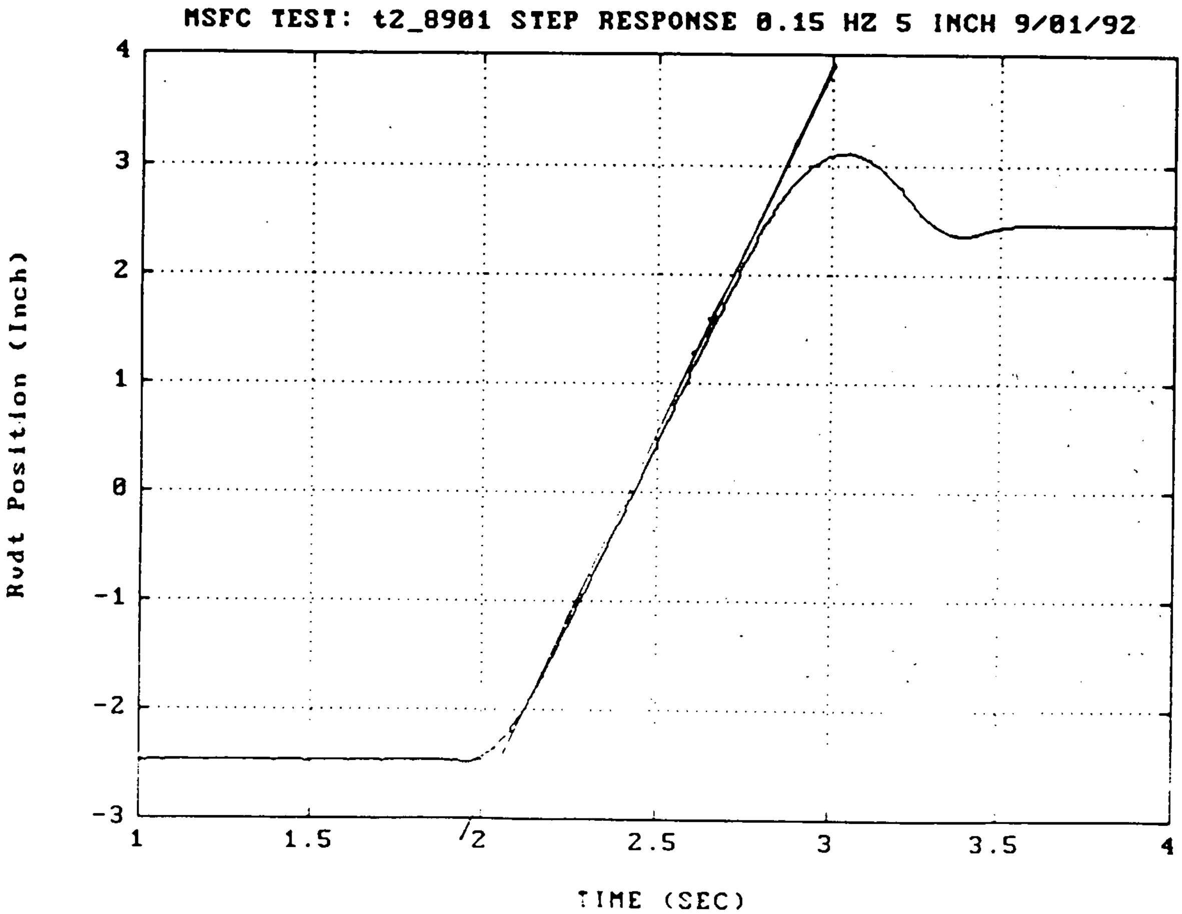
MSFC 25 H.P. Actuator System Block Diagram



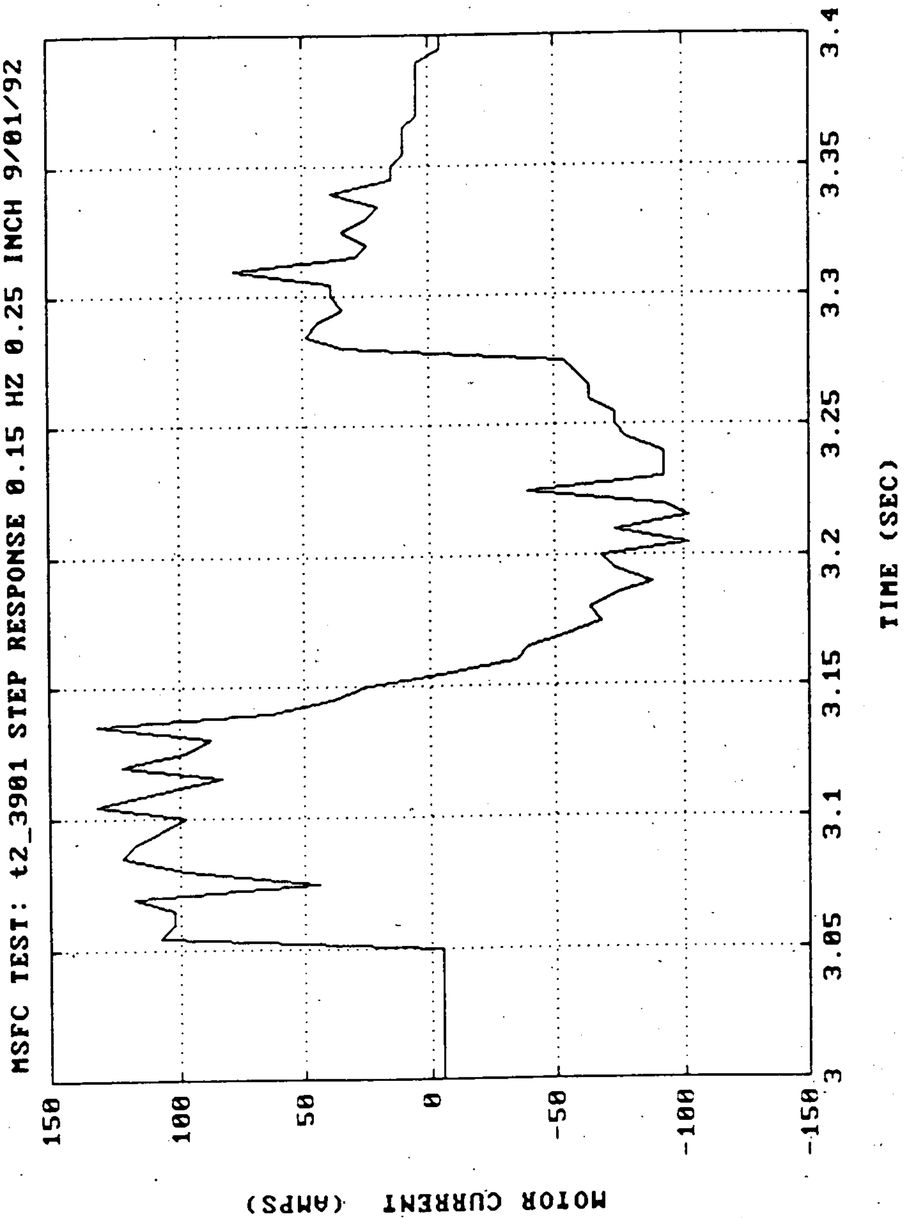
Simulated Frequency Response

THESE ARE EXAMPLES OF BOTH SMALL AND LARGE STEP RESPONSES. THE SMALL STEP SHOWS AN OVERSHOOT OF 16 PERCENT AND ALSO MEETS THE SSME SMALL STEP REQUIREMENTS. THE LAYER STEP HAS A 13 PERCENT OVERSHOOT. THE MAXIMUM RATE IS ALMOST 7 IN/SEC WHICH EXCEEDS THE DESIGN REQUIREMENT.

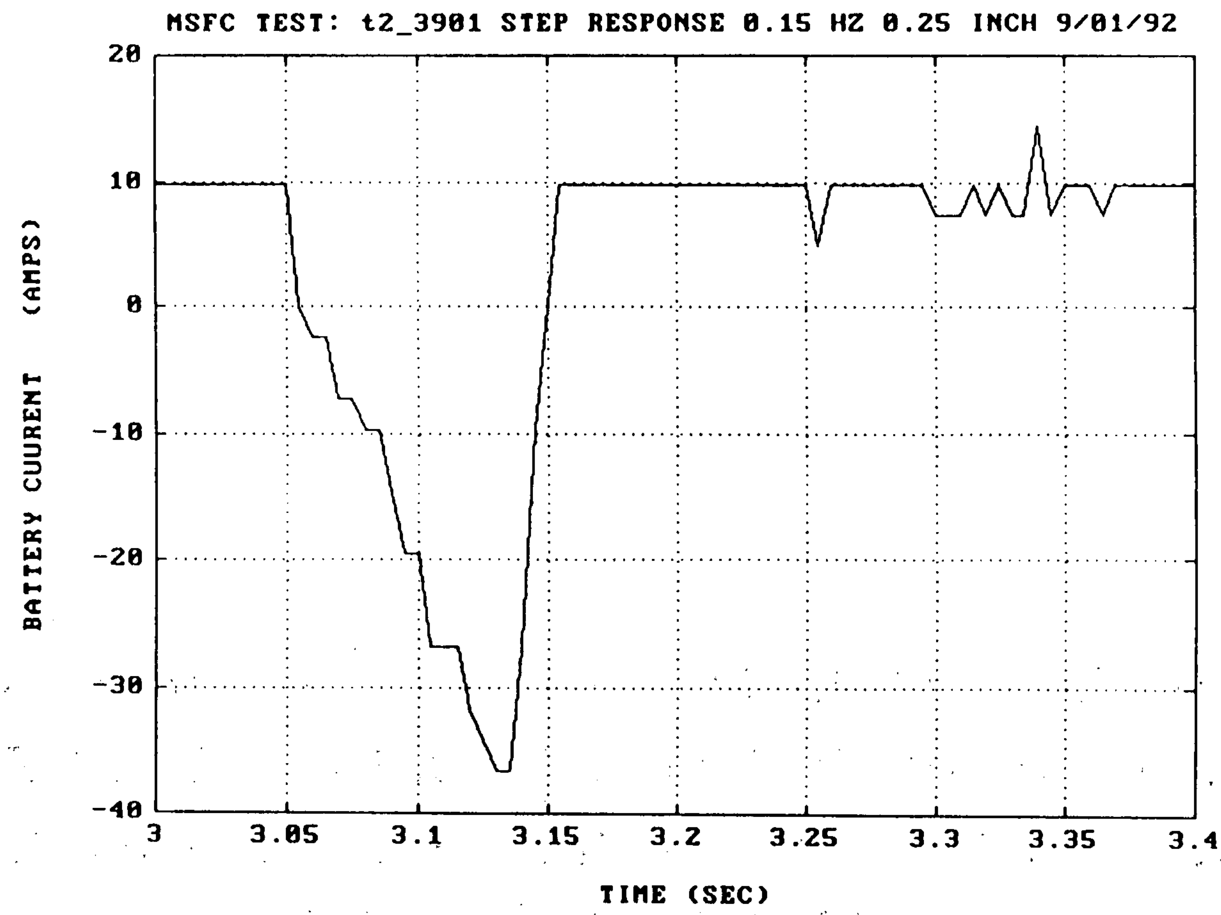

MSFC TEST: t2_3901 STEP RESPONSE 0.15 HZ 0.25 INCH 9/01/92
Rvdt Position (Inch)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
12.4
12.6
12.8
13
13.2
13.4
13.6
13.8
14
TIME (SEC)


MSFC TEST: t2_8901 STEP RESPONSE 0.15 HZ 5 INCH 9/01/92
Rvdt Position (Inch)
4
3
2
1
0
-1
-2
-3
1
1.5
2
2.5
3
3.5
4
TIME (SEC)

THE NEXT TWO VIEWGRAPHS COMPARE MOTOR AND BATTERY CURRENT FOR THE 0.25 INCH STEP. THE POLARITY ON BATTERY CURRENT IS REVERSED AND SLIGHTLY OFFSET, BUT THE TIME AXES ARE IDENTICAL. THIS SHOWS THAT THE CAPACITOR ON THE CONTROLLER ACCOMMODATES THE INITIAL CURRENT REQUIREMENT. ONE CAN SEE BATTERY CURRENT RAMPS UP AND THERE IS NOT A LARGE INSTANTANEOUS CURRENT DRAIN FROM THE POWER SOURCE. ALSO, NOTE THAT BATTERY CURRENT IS NOT REQUIRED DURING THE BRAKING PORTION OF THE STEP RESPONSE, EVEN THOUGH THE MOTOR ITSELF CONTINUES TO CARRY CURRENT IN THE REGENERATION MODE.

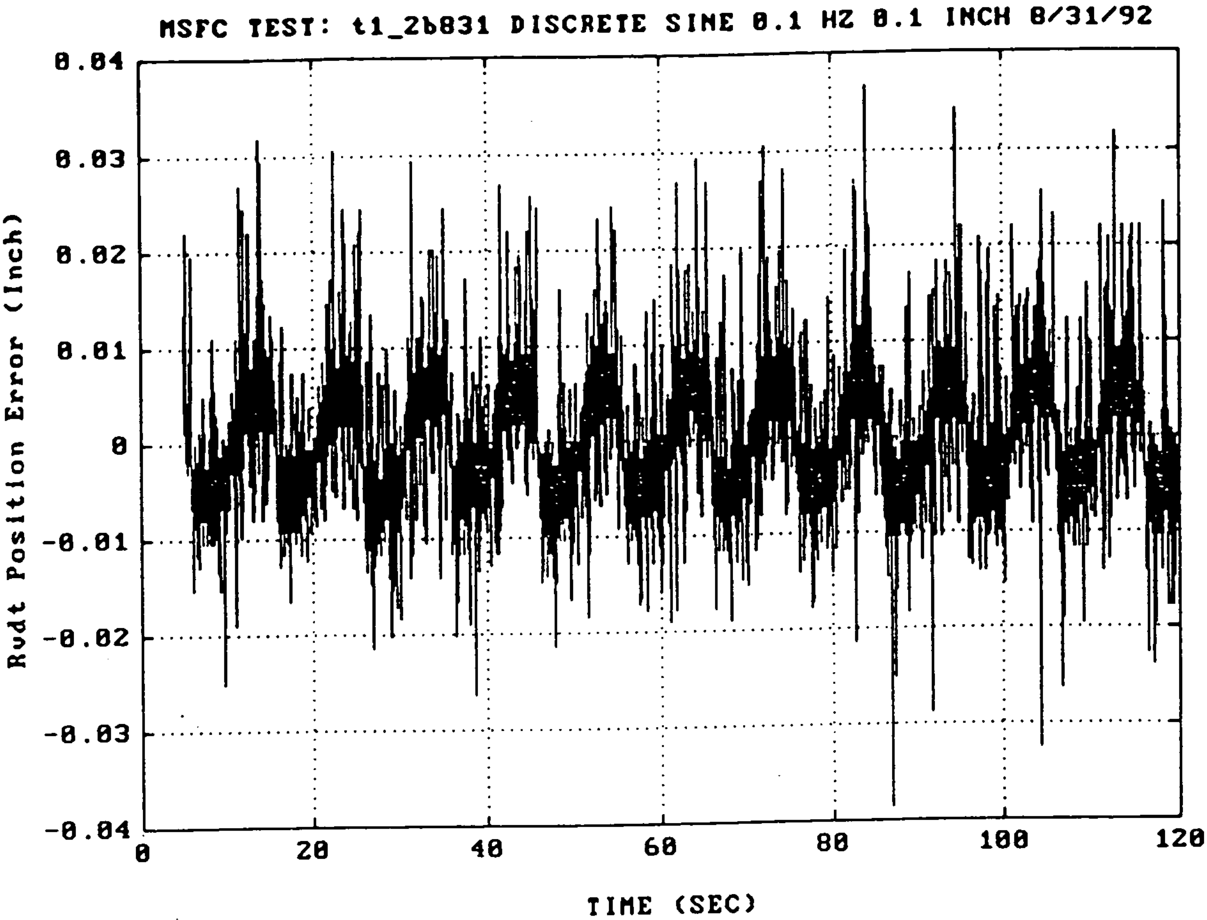


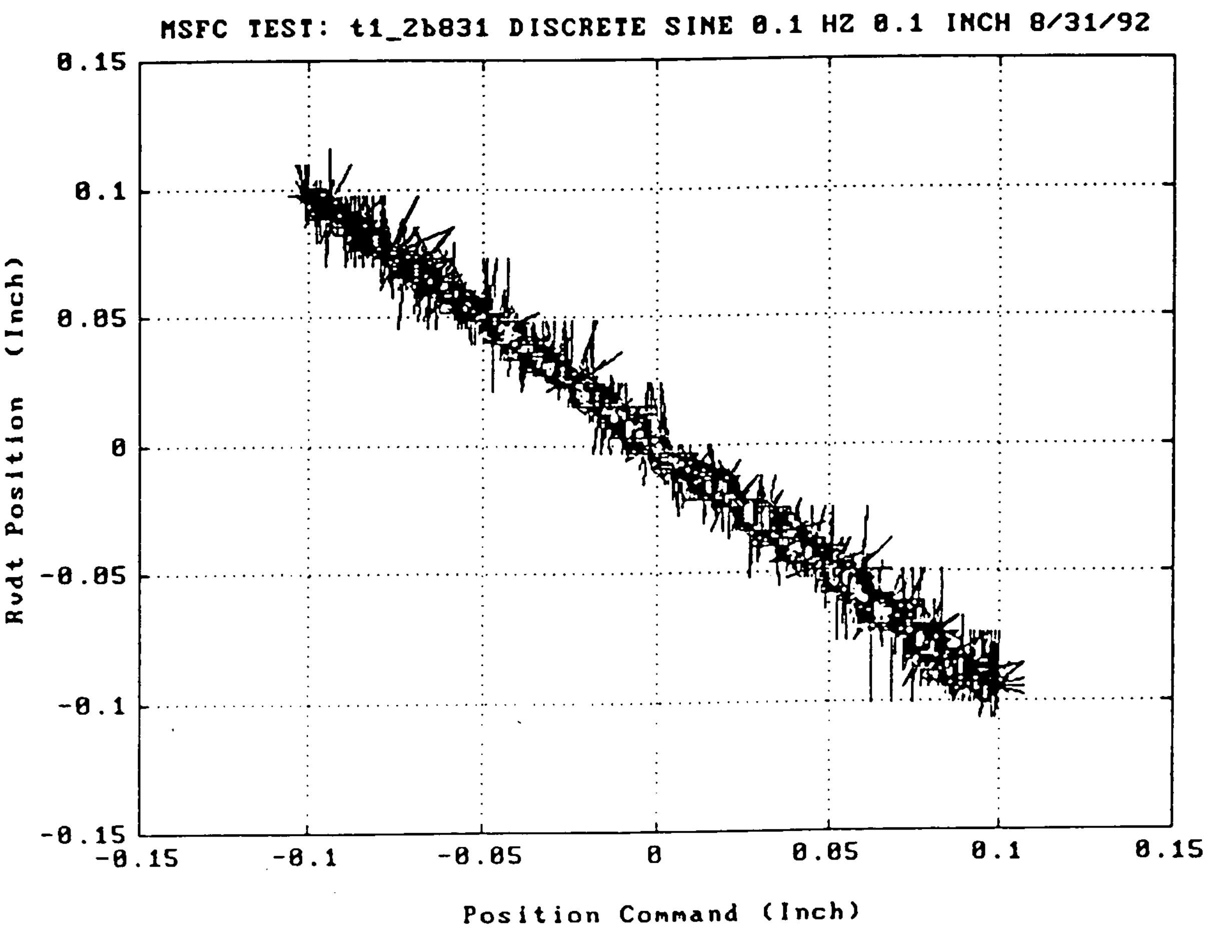
Motor Current

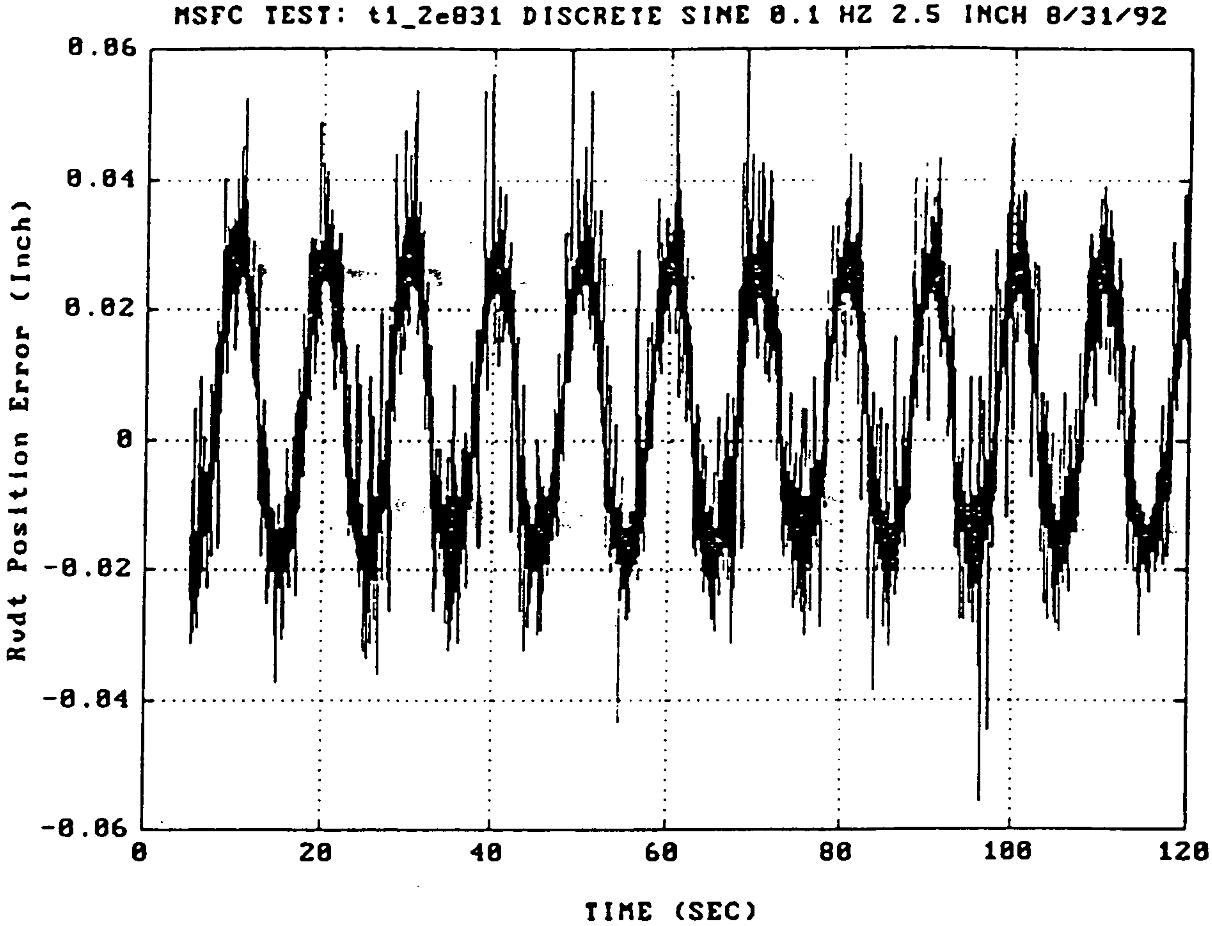


Battery Current

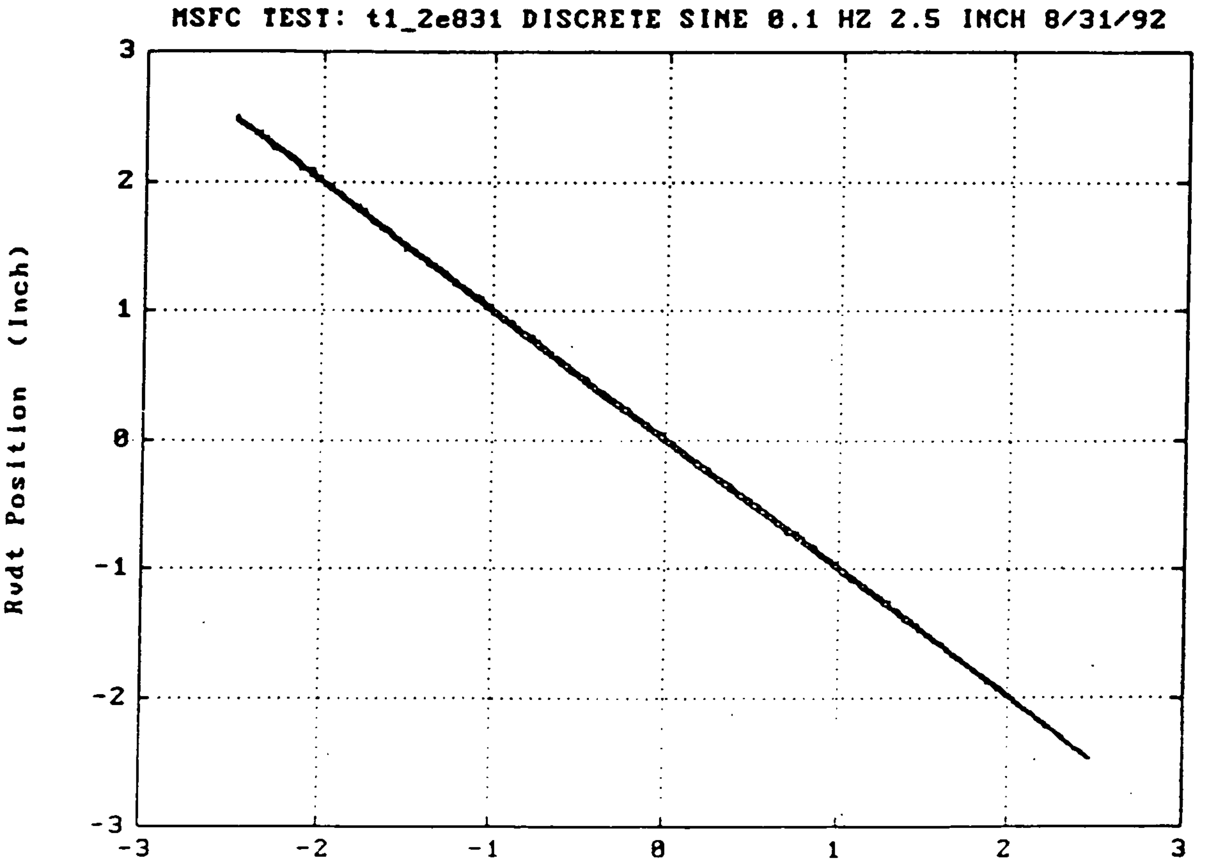
THE NEXT TWO VIEWGRAPHS SHOW LINEARITY FOR BOTH SMALL AND LARGE EXCURSIONS. THE POSITION ERROR FALLS WITHIN THE NOISE OF THE DATA AND MEETS THE 0.050 INCH ACCURACY REQUIRED, WITH THE LARGE EXCURSION ERROR BEING ABOUT 0.030 INCH.


MSFC TEST: t1_2b831 DISCRETE SINE 0.1 HZ 0.1 INCH 8/31/92
Rvdt Position Error (Inch)
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0
20
40
60
80
100
120
TIME (SEC)


MSFC TEST: t1_2b831 DISCRETE SINE 0.1 HZ 0.1 INCH 8/31/92
Rvdt Position (Inch)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
Position Command (Inch)

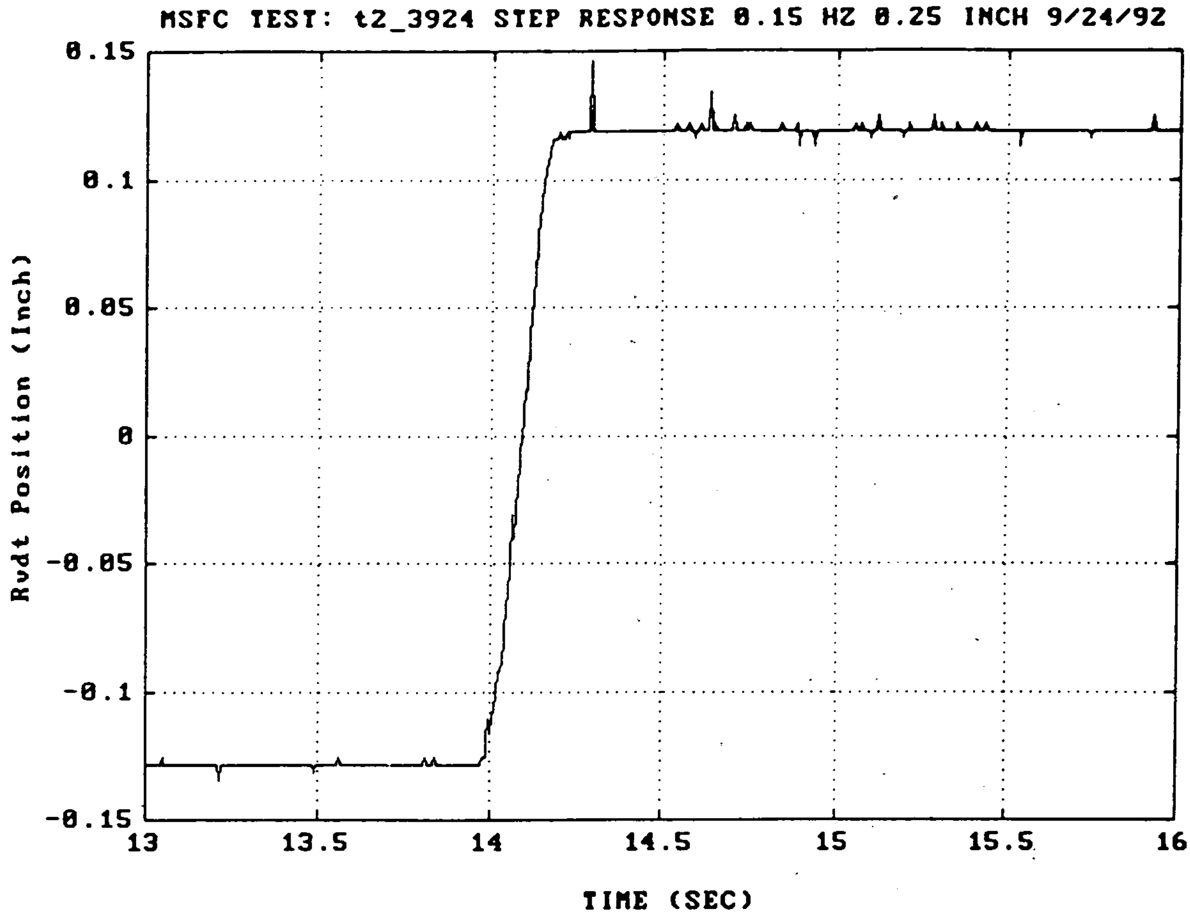


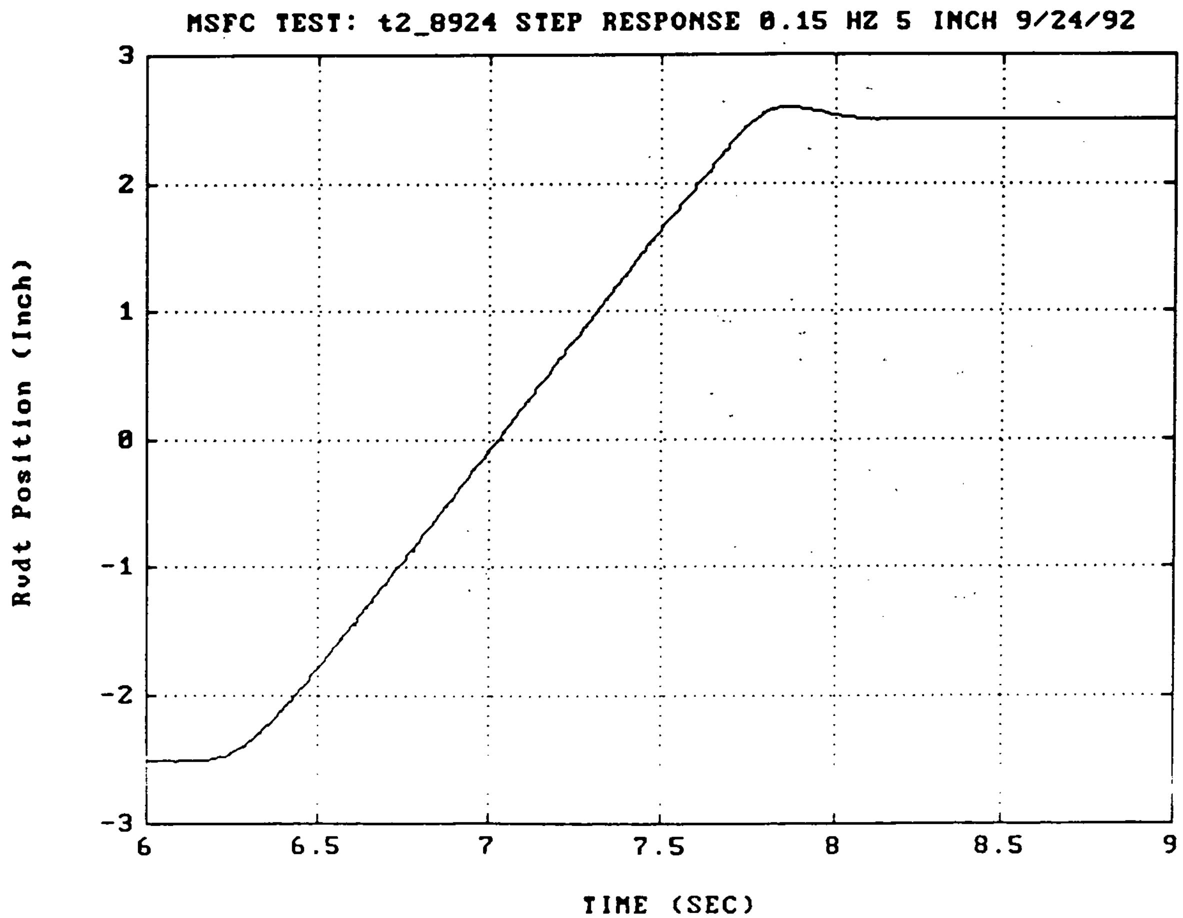
MSFC TEST: t1_2e831 DISCRETE SINE 0.1 HZ 2.5 INCH 8/31/92
Rvdt Position Error (Inch)
TIME (SEC)
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
0
20
40
60
80
100
120



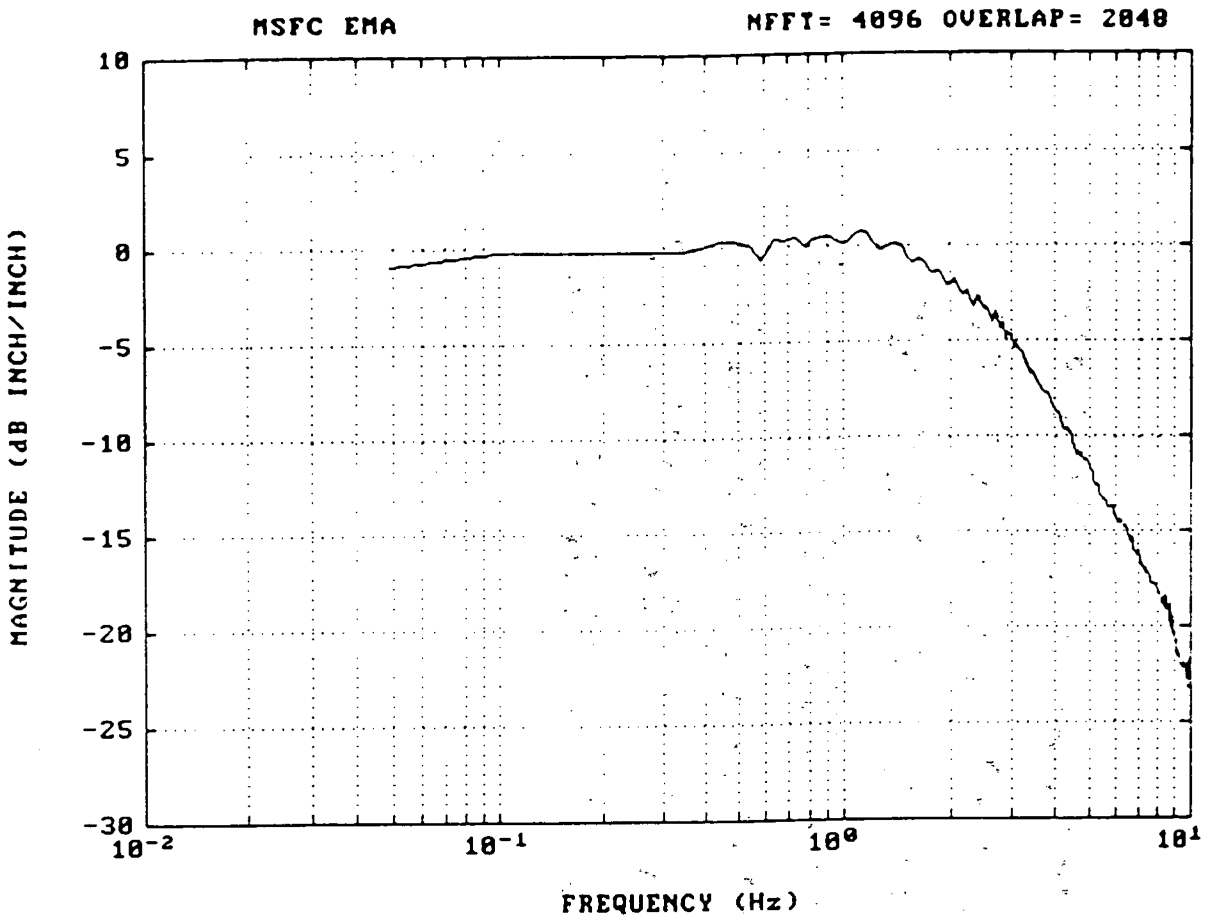
MSFC TEST: t1_2e831 DISCRETE SINE 0.1 HZ 2.5 INCH 8/31/92
Rvdt Position (Inch)
3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2
3

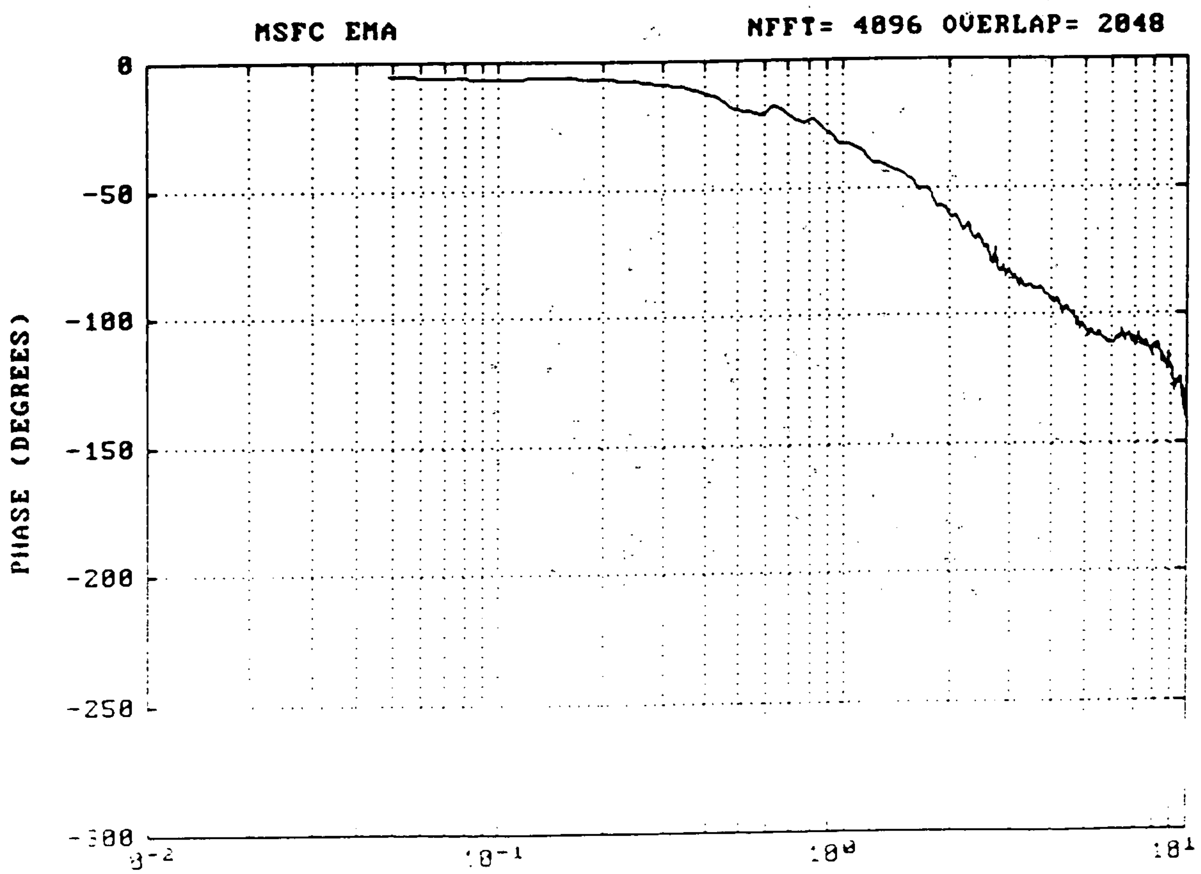
AFTER COMPLETION OF THE TEST PLAN ON THE INITIAL CONTROLLER CONFIGURATION, IT WAS DECIDED TO IMPLEMENT A RATE LOOP. PRELIMINARY RESULTS EFFECTIVELY REDUCE THE OVERSHOOT BUT SHOW THE MAXIMUM RATE WAS REDUCED TO LESS THAN 4 IN/SEC AND ALSO A REDUCTION IN BANDWIDTH. THE NEXT STEP WILL BE TO TUNE THE RATE LOOP TO MEET ALL DESIRED SPECIFICATIONS.



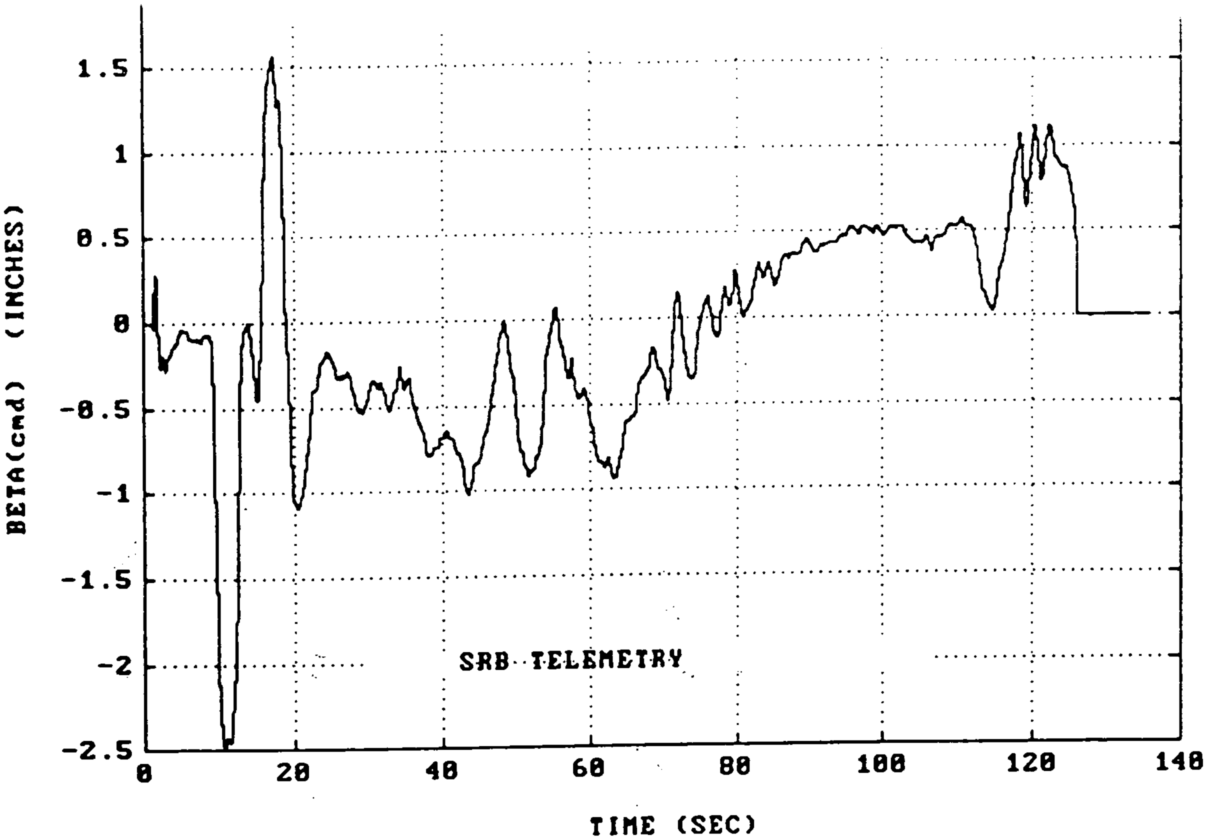


Step Response With Rate Loop

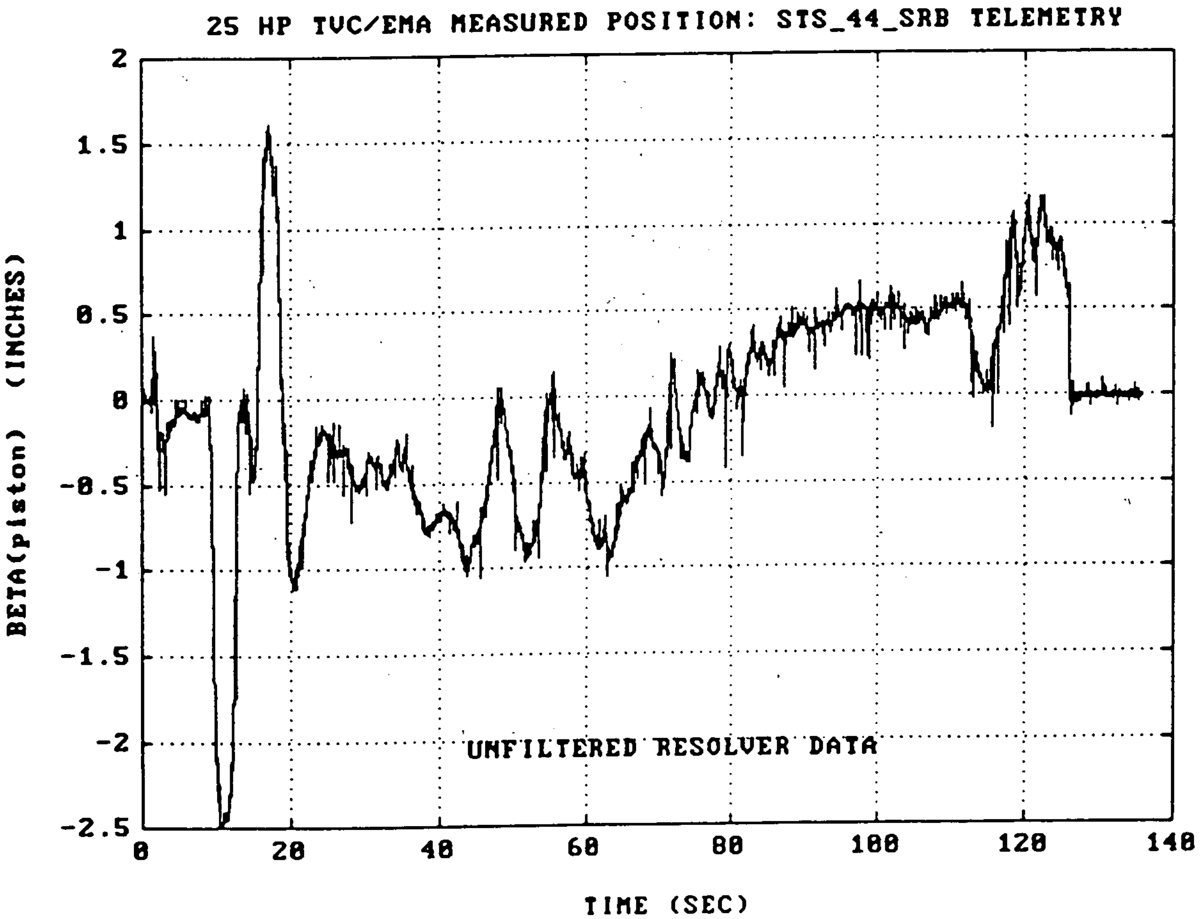

MSFC EMA
NFFT= 4096 OVERLAP= 2048
MAGNITUDE (dB INCH/INCH)
10
5
0
-5
-10
-15
-20
-25
-30
10^-2
10^-1
10^0
10^1
FREQUENCY (Hz)


MSFC EMA
NFFT= 4096 OVERLAP= 2048
PHASE (DEGREES)
0
-50
-100
-150
-200
-250
-300
10^-1
10^0
10^1

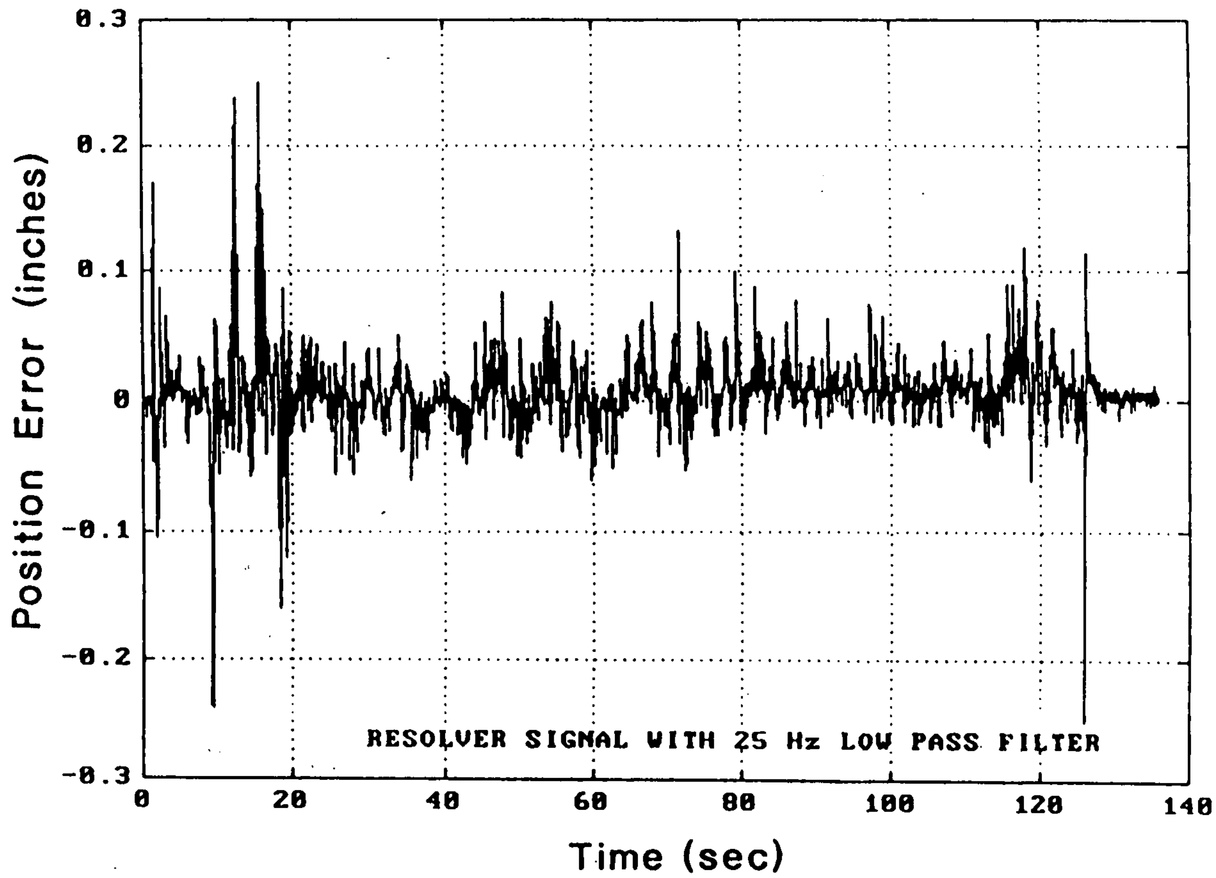
THIS VIEWGRAPH SHOWS THE STS-44 SRB COMMAND PROFILE AND THE TVC/EMA RESPONSE. THE NEXT VIEWGRAPH SHOWS THE POSITION ERROR BETWEEN COMMAND AND RESOLVER DATA FOR THE ACTUATOR. IN COMPARISON TO THE ACTUAL HYDRAULIC DATA, THE EMA ERROR IS SMALLER, ALTHOUGH FOR THE EMA SYSTEM NO FLIGHT TYPE LOADS (WIND GUSTS, ETC.) WERE APPLIED.



STS - 44- SRB Command Profile



PRELIMINARY 25 HP TVC/EMA RESPONSE TO STS-44-SRB COMMAND PROFILE



Position Error of 25 H.P. TVC EMA For Command Profile

A NEW GEAR SYSTEM IS ON ORDER WHICH WILL ALLOW MSFC TO IMPLEMENT A TWO MOTOR CONFIGURATION ON THIS ACTUATOR. WHILE AWAITING DELIVERY OF THESE GEARS, THE RATE AND POSITION LOOPS OF THE CONTROLLER WILL BE TUNED TO MEET ALL DESIRED SPECIFICATIONS. TESTING WILL RESUME WITH DATA BEING USED TO VALIDATE THE ACTUATOR MODEL. THIS MODEL WILL BE USED FOR SIMULATION IN ADDITION TO TEST DATA TO DEFINE AND IMPLEMENT A REDUNDANCY MANAGEMENT SCHEME FOR THE TWO MOTOR ACTUATOR.

FUTURE PLANS

- Tune rate and position loops to meet desired specifications
- Demonstrate Rate vs Load capability
- Demonstrate Simulated Flight Load Capability
- Use test data to validate model
- Implement a two motor configuration
- Using model and test data, define and implement redundancy management scheme

ITW Spiroid
An Illinois Tool Works Company
2801 North Keeler Avenue
Chicago, Illinois 60639
Telephone 312.227.2200
FAX 312.227.0535

ITW Spiroid

ITW SPIROID

ITW Spiroid, A Division of Illinois Tool Works, is a manufacturer of proprietary, custom gear forms, roller screws, and index rings. These products come in the form of Spiroid + Helicon right angle gearing, Concurve spur gears, Spiracon roller screws, and Endicon index rings.

ITW Spiroid provides their products for a large number of diverse applications. Approximately 50% of our volume goes to both military and commercial markets. Military applications include such equipment as the Apache Helicopter, M109 Howitzer, F15 Fighter Aircraft, and the Harpoon and RAM Missiles. Commercial applications include Hand Tools, Laser Imaging Devices, Machine Tool + Fixturing Devices, Tundish Car Actuators, and Aircraft Flap Actuators.

Spiroid/Helicon - Right Angle Gearing

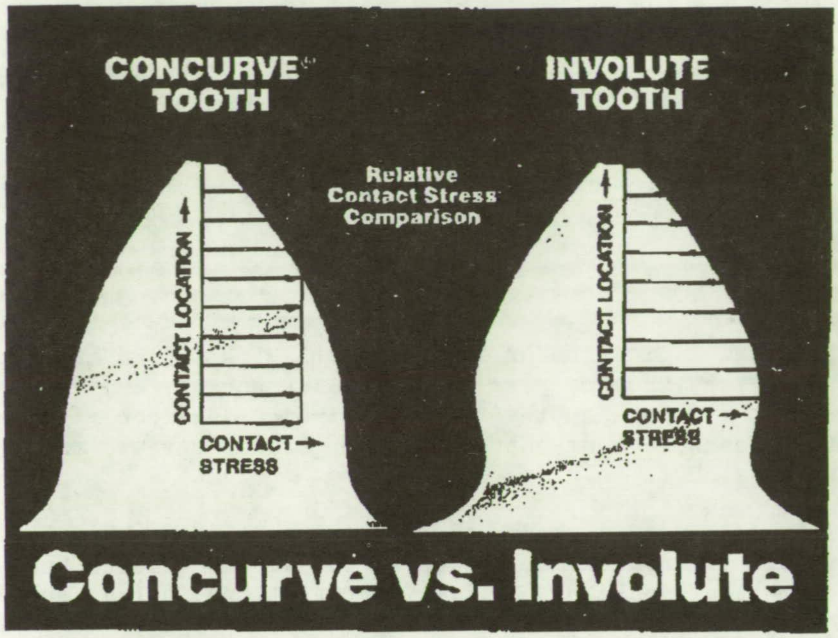
Spiroid	Helicon
10:1 - 400:1	4:1 - 400:1
High Contact Ratio	High Contact Ratio
Higher Capacity	High Capacity
Good Efficiency	Better Efficiency

Possible Cross Shaft Design
Backlash Control
Material Variability

These gear forms have the widest center distance of any right angle, face type gear form thereby producing the highest contact ratios possible. This allows for high capacity in small space envelopes thus affecting packaging, weight, and power density.

Concurve Spur Tooth Gears

This gear form is a variation of an involute spur tooth form where the tooth profile has a relatively constant radius of curvature from the tip of the tooth to the root of the tooth. This distributes the contact stress evenly up + down the tooth flank. Involute spur gear teeth tend to have ever increasing contact stress as you move from tip to root of the tooth.



The even distribution of stress in Concurve gears allows for higher loads and lower numbers of pinion teeth due to this feature. Therefore, pinions with as few as 4 teeth and ratios up into the 20's:1 are possible. Removal of gear passes, higher loads, higher ratios and downsizing are all possible.

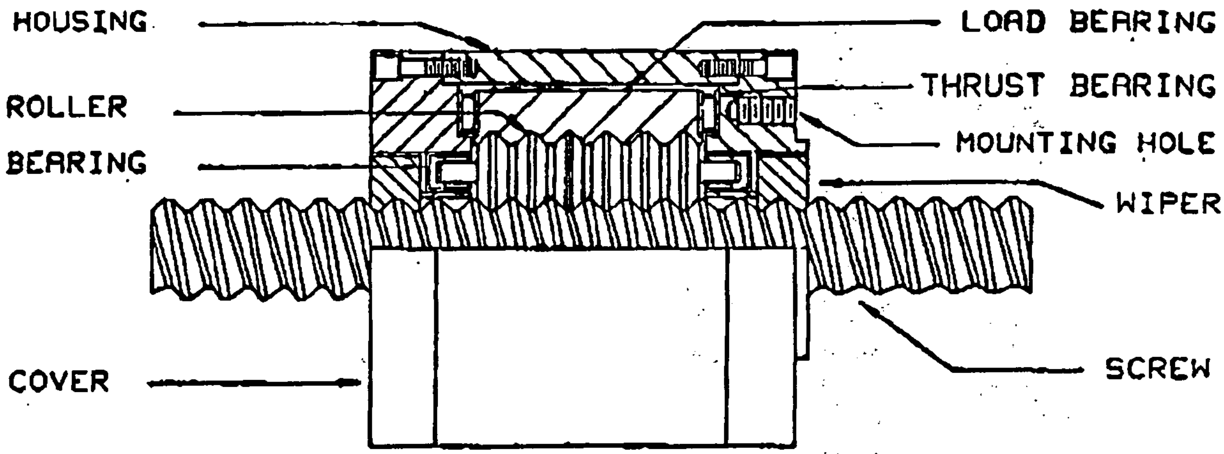
Spiracon Roller Screws

Spiracon Roller Screws offer several advantages over Ball Screws and Acme Screws. The basis for these advantages lie in a discussion of the type of contact that exists between members within the nut itself.

Acme Screws have line contact between members. They have great capacity for this reason. However, there is so much contact and with the elements sliding upon each other, the efficiency is extremely low, usually around 20%. Thus motors tend to be very large to overcome this inefficiency.

Ball screws have point type contact between members. Imagine a ball riding in a trough of slightly larger curvature. A small point exists between these two members upon which the load will be carried. For this reason they have limited capacity. However, due to this small contact area and the rotation of all internal components, ball screws are generally very efficient.

Spiracon Roller Screws have line type contact between members. These lines create a large area over which the load is carried thus decreasing the stresses on the components. Higher capacities, longer life and reduced size are all possible. All internal components do rotate however, because of the increase in contact area, roller screws are slightly less efficient that ball screws.



SPIRACON® ROLLER SCREW

Endicon Index Rings

Endicon Index Rings consist of 2 mirror image gear halves with teeth machined such that intimate contact exists between the two halves. They can be used as indexing devices, couplings, centering devices, etc. They have been used previously in such applications as Indexing Tables, Multi-Stage Turbine Blade Alignment devices, Robotic end effector joints and Blind Assembly Robotic couplings.

NATIONAL LAUNCH SYSTEM TURBOALTERNATOR PSS DEMONSTRATOR UNIT

SEPT. 29, 1992

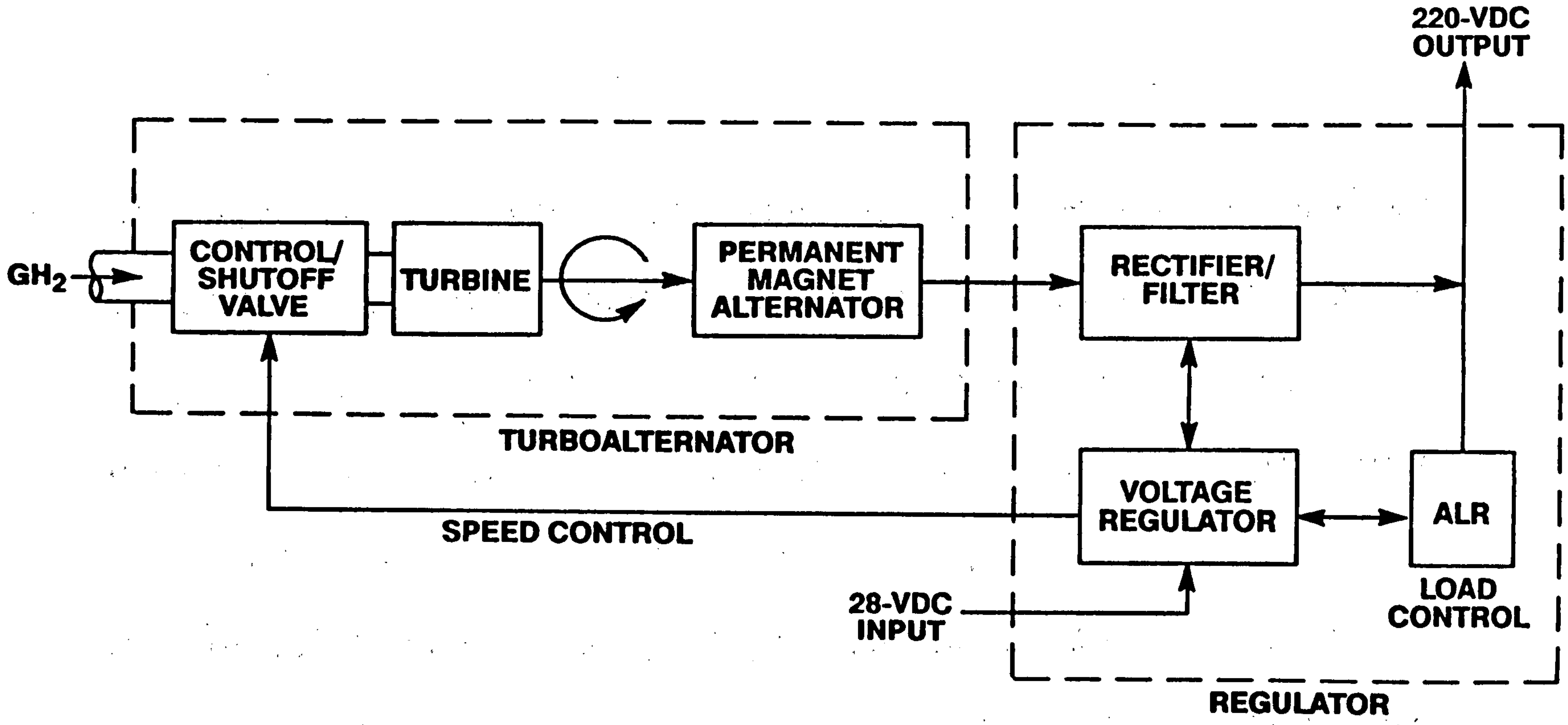
Allied-Signal Aerospace Company
AiResearch Los Angeles Division

Allied Signal

HIGH-SPEED, DIRECT-DRIVE TURBINE-DRIVEN PSS

The basic components of the PSS are shown here along with how they interface with each other and the exterior load.

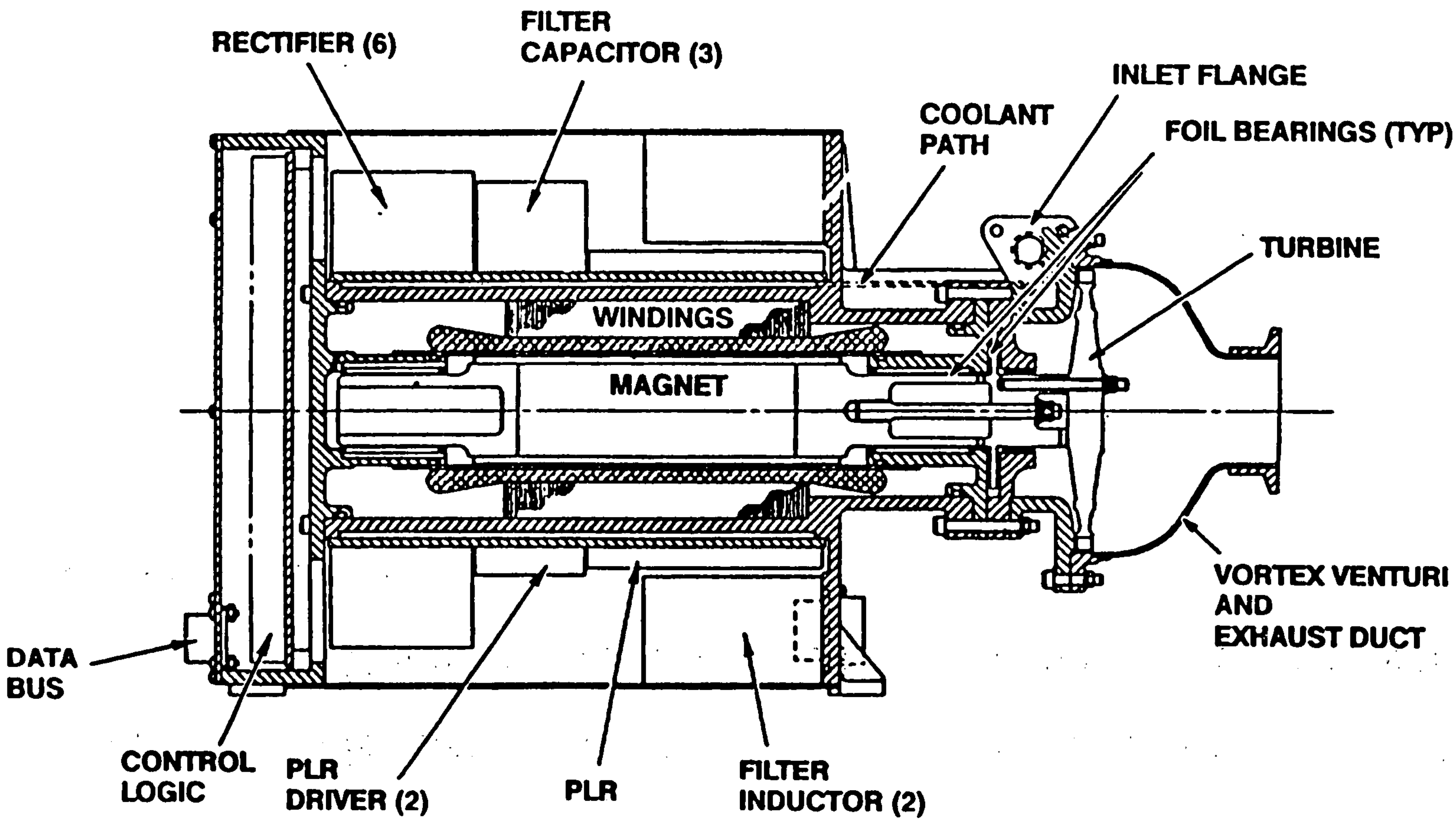
HIGH–SPEED PSS BLOCK DIAGRAM



IG-11197-A

This cross section of the hydrogen powered PSS turboalternator shows the single two pole toothless alternator rotor directly driven by the single stage axial impulse turbine. A vortex venturi provides passive overspeed protection. Also shown are the radial and the axial foil bearings. The electrical power conditioning and speed control electronics are installed around the periphery of the turboalternator. All cooling is provided by the gaseous hydrogen.

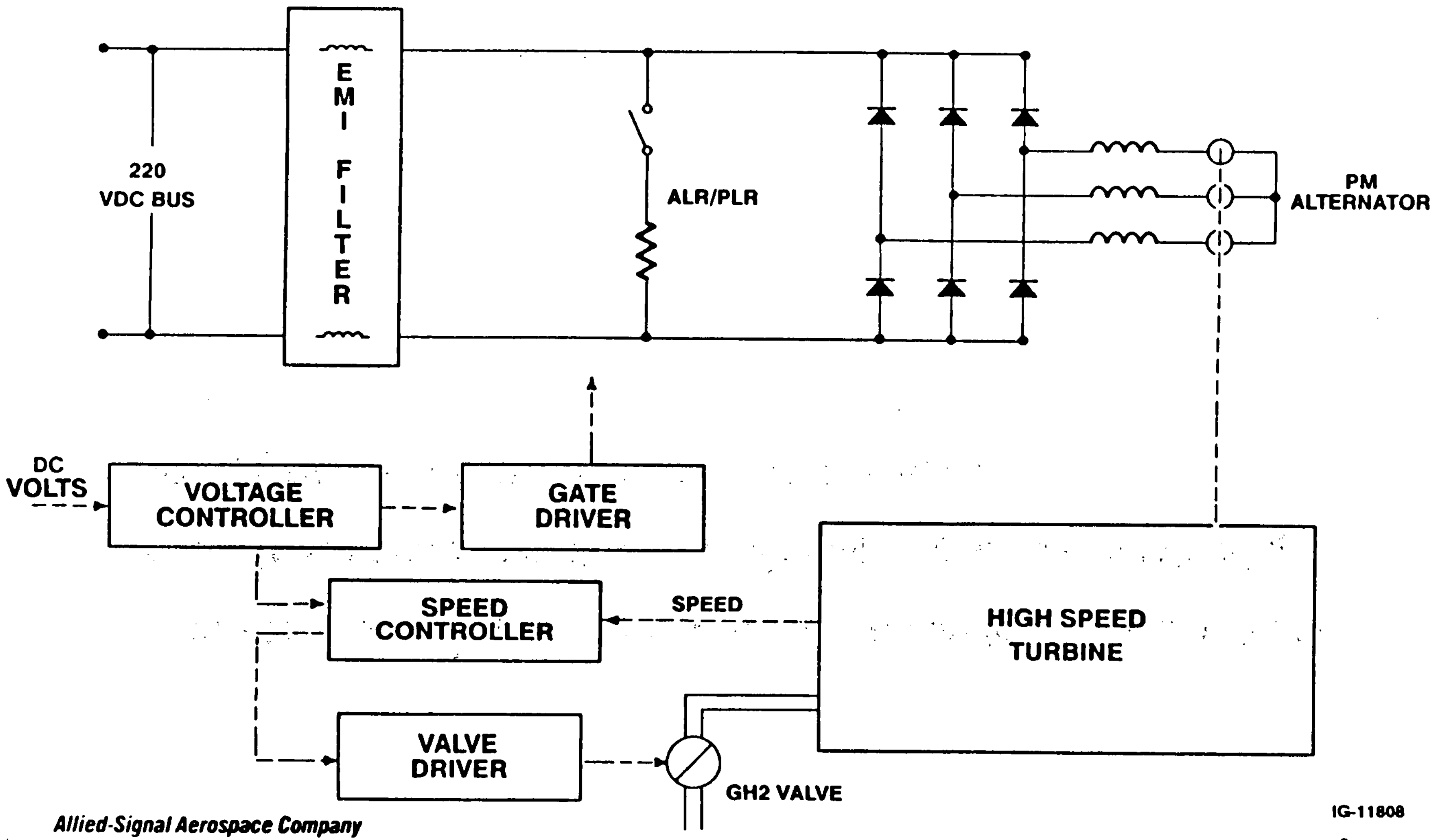
HIGH-SPEED PERMANENT-MAGNET ALTERNATOR PSS CROSS SECTION



IG-11198-A

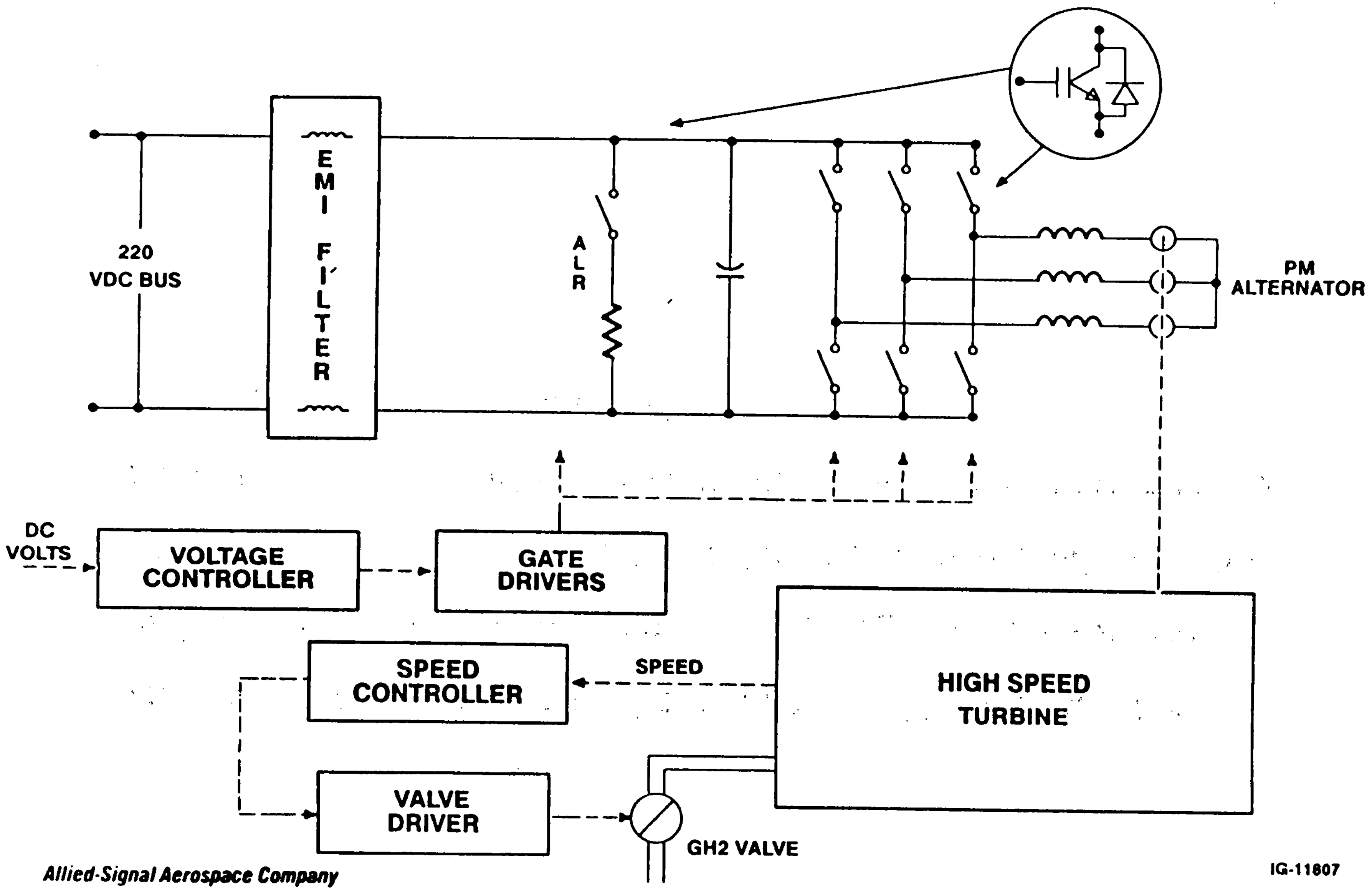
This schematic shows the simple rectifier design power conditioner. The output voltage level is a function of the electrical load and the rpm.

HIGH SPEED PSS WITH RECTIFIER



This alternate inverter-type power conditioner is less dependent on rpm. The inverter operates in an upchopping mode, eliminating voltage droop due to speed and load changes.

HIGH SPEED PSS WITH INVERTER

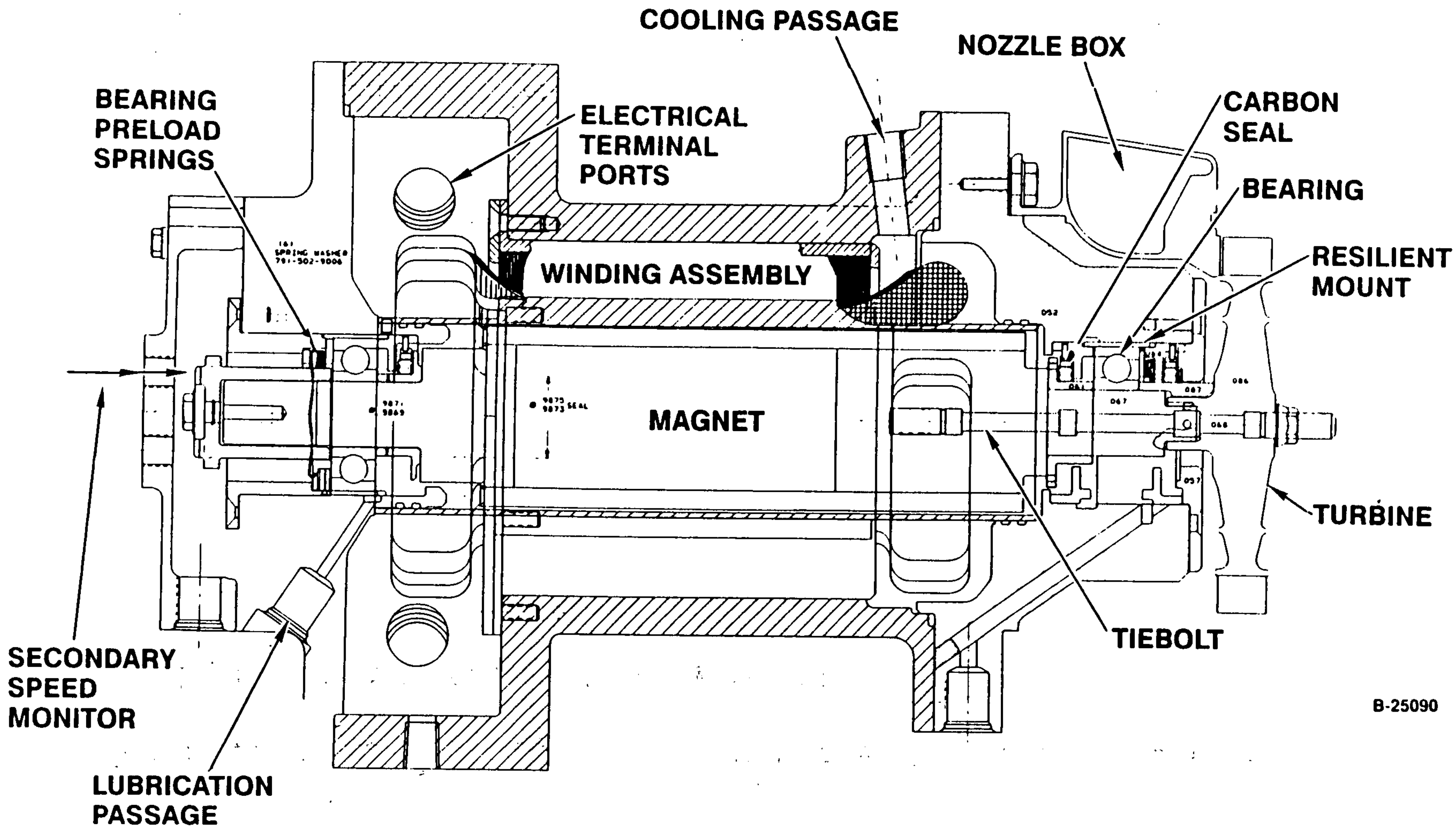


IG-11807

Allied-Signal Aerospace Company
AiResearch Los Angeles Division
AlliedSignal

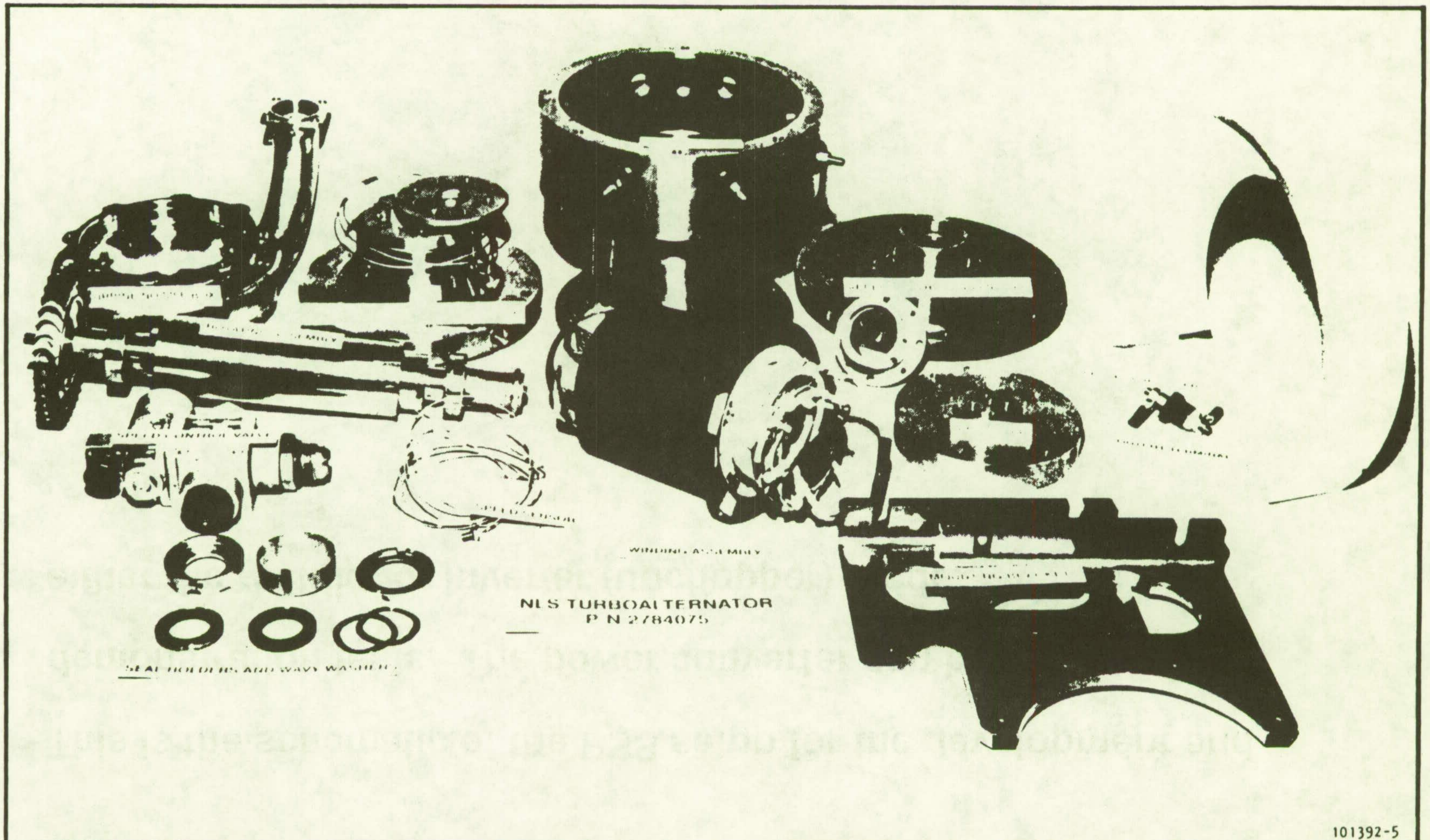
This is a cross-section of the helium powered turboalternator demonstration unit. It consists of heavy hogged out structures and utilizes oil mist lubricated angular contact ball bearings. The arrangement of the turboalternator components is similar to that of the hydrogen demonstrator unit.

NLS PSS TURBOALTERNATOR



Pictured are the details and subassemblies which make up the PSS helium demonstrator turboalternator.

NLS TURBOALTERNATOR
P/N 2784075



101392-5

F-65574

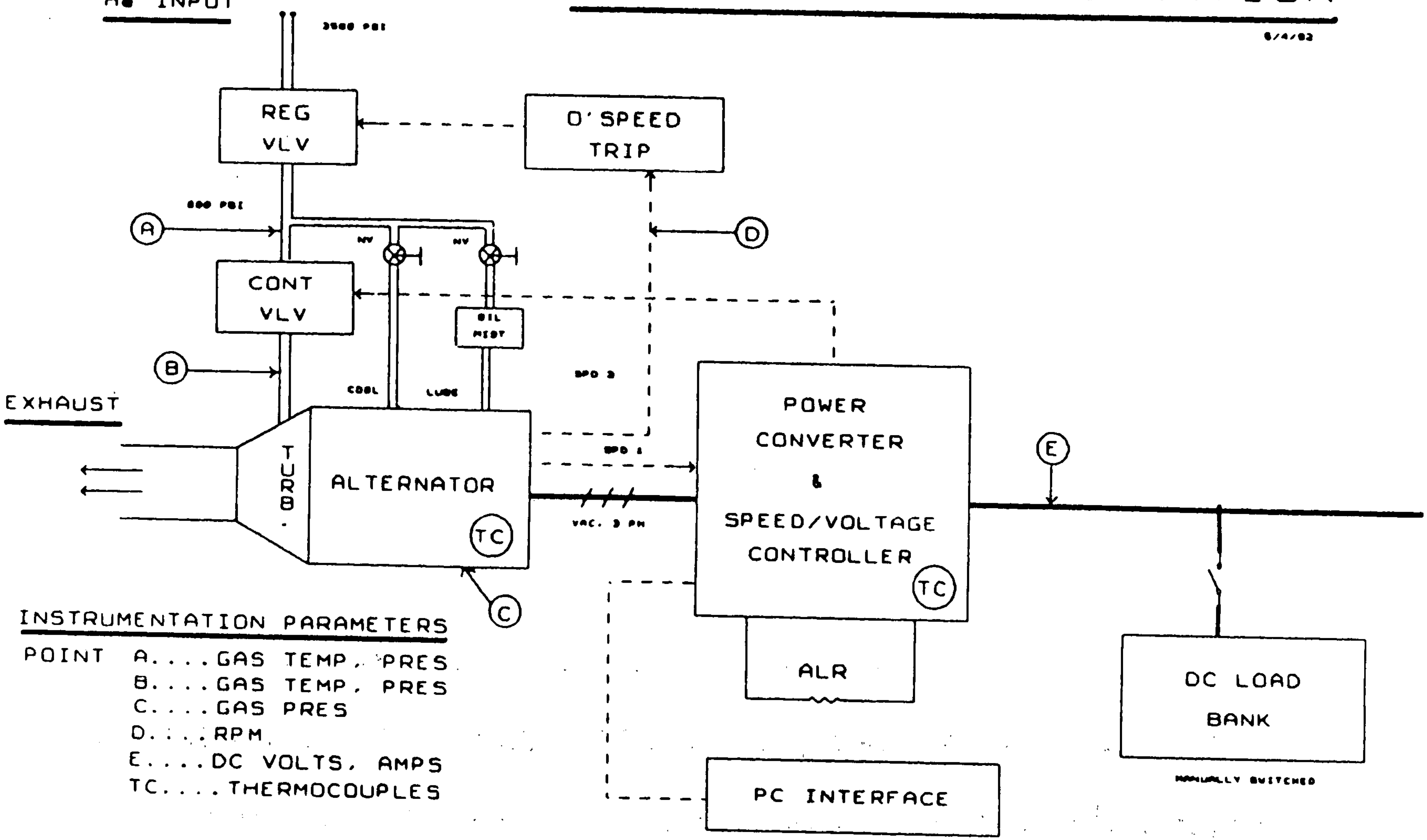
Allied-Signal Aerospace Company

AiResearch Los Angeles Division

C-7

This is the schematic of the PSS setup for the development and demonstration tests. The power converter can be operated in either the rectifier or inverter (upchopper) mode.

PSS LAB DEMONSTRATION



INSTRUMENTATION PARAMETERS

POINT A....GAS TEMP, PRES
B....GAS TEMP, PRES
C....GAS PRES
D....RPM
E....DC VOLTS, AMPS
TC....THERMOCOUPLES

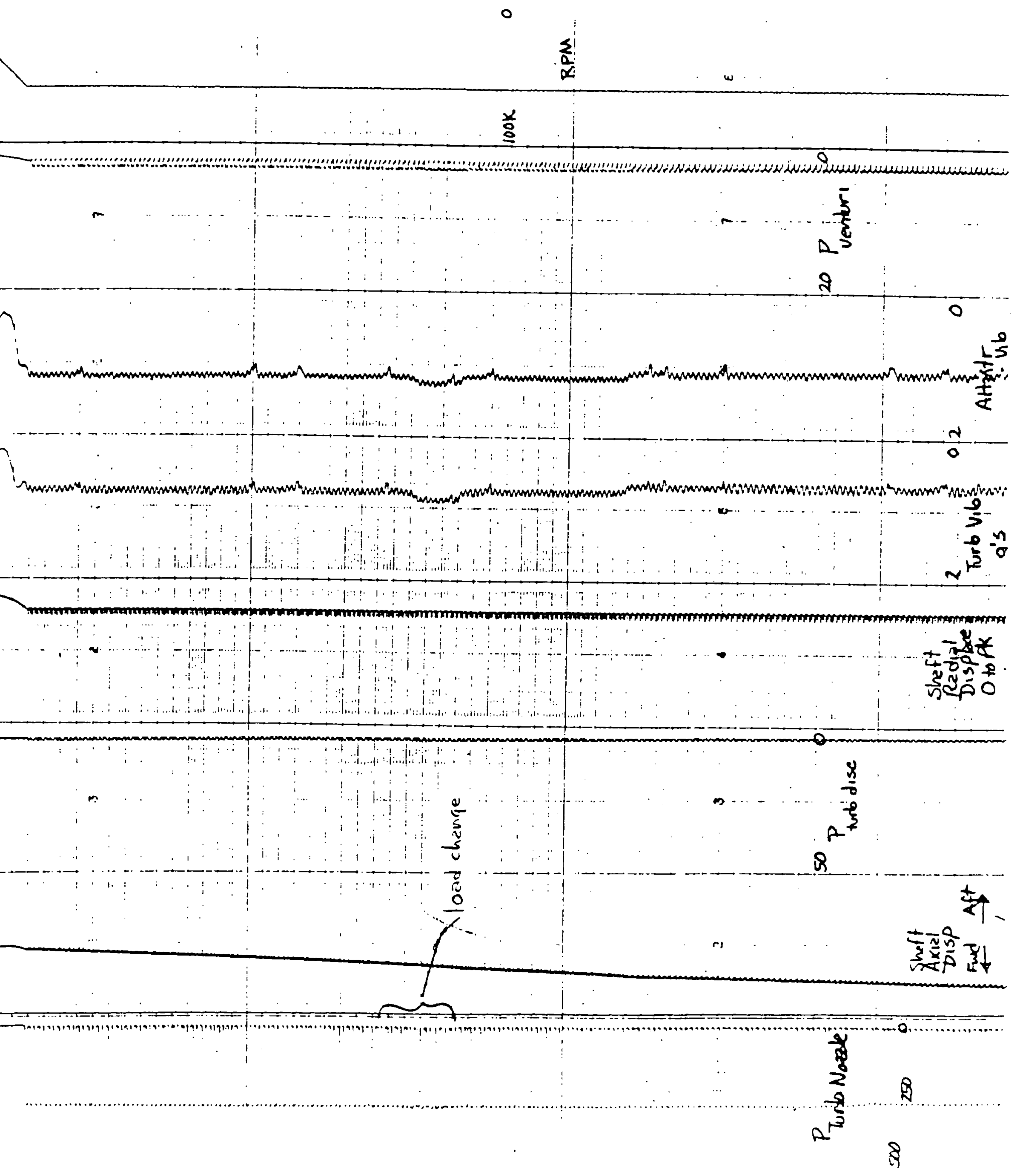
The majority of these tests have been accomplished. Application and shedding of the maximum electrical load as a step function under various conditions is not yet complete.

GHe TEST PLAN OVERVIEW

- VIBRATION SURVEYS
- VORTEX VENTURI EFFECTIVENESS
- TURBINE PERFORMANCE
- WINDING RESISTANCE AND INDUCTANCE
- NO LOAD VOLTAGES
- SPINDOWN TESTING
- STEADY STATE LOADS
- TRANSIENT LOADS
- LOAD REGULATION
- OPERATING AND SOAKBACK TEMPERATURES
- PRESSURE DIFFERENTIALS

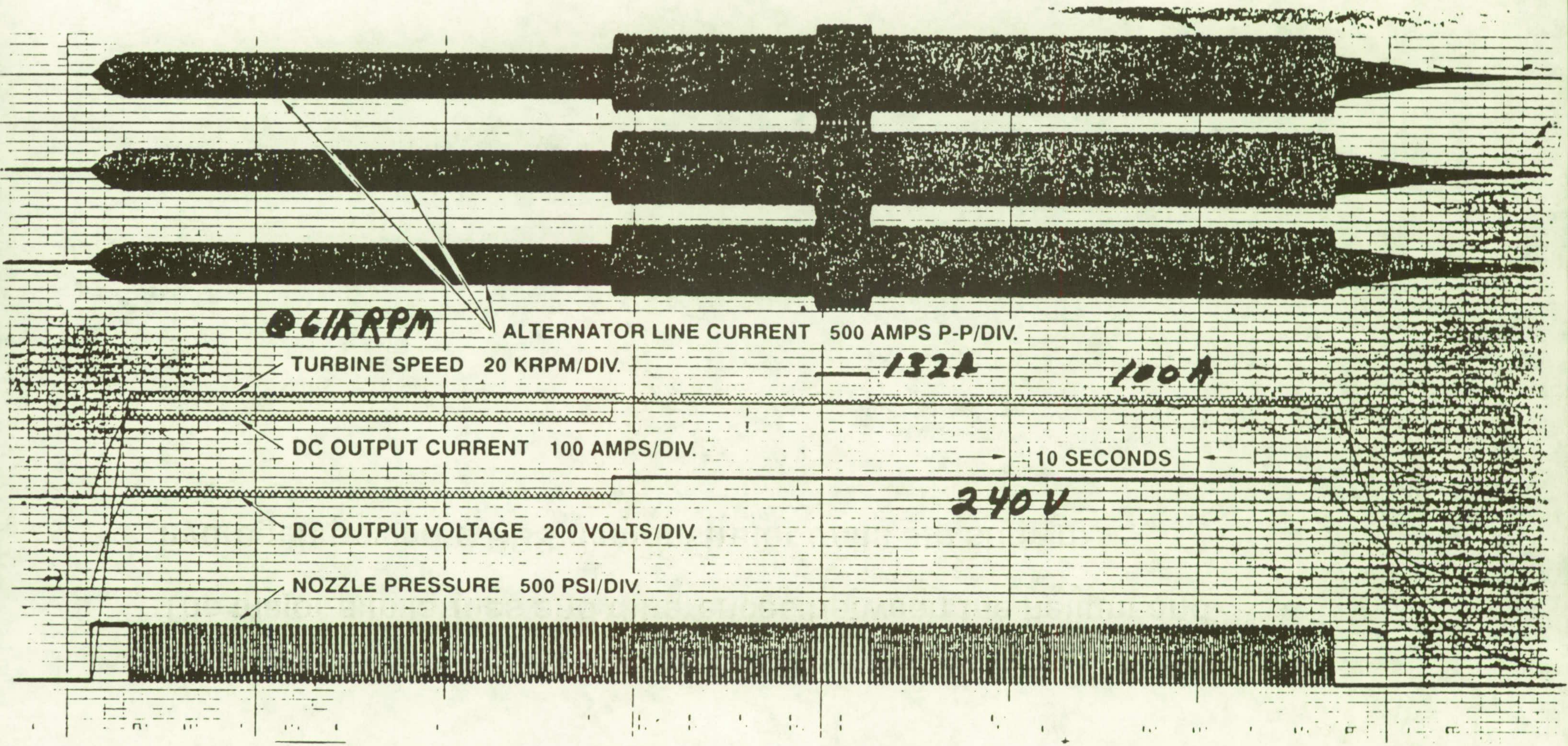
IW-17887

Shown here are the traces of rpm and helium pressure to the turbine as the turboalternator; was started up under load, was run in the rectifier mode, accomplished an output voltage (and current) increase by switching to the upchopper mode, had additional partial load applied and shed as step changes, and was shut down.


RPM
100K
0
P venturi
20
Alternator Vib
Turb Vib g's
Shaft Radial Displace 0 to Pk
P turb disc
50
load change
Shaft Axial Disp
Fwd
Aft
P Turb Nozzle
250
500

This is another stripchart recording of the test described on the previous page. It shows traces of the currents, DC output voltage, rpm and turbine nozzle pressure. The output voltage is closely regulated during the load changes.

BOEING/ALLIED-SIGNAL
GHe 2 TURBO ALTERNATOR



The major similarities and differences between the helium and hydrogen powered PSS demonstrator units are shown.

PSS TURBOALTERNATOR DESIGN COMPARISONS

	Helium Demonstrator	Hydrogen Demonstrator
Power Output	35 kw at 220 vdc	35 kw at 220 vdc
RPM	65,000	60,000
Voltage Control	Rectifier & Upchopper	Rectifier or Upchopper
Speed Control Valve	Limit Cycling	Proportional
Bearings	Ball/Oil Mist	Foil/GH_2
Weight	180 lbs.	75 lbs.
Packaging	Two Separate Components	Wrap-Around Electronics

THE CAPABILITY TO DEVELOP THE REQUIRED 35 KW ELECTRICAL POWER HAS BEEN DEMONSTRATED

SESSION IX

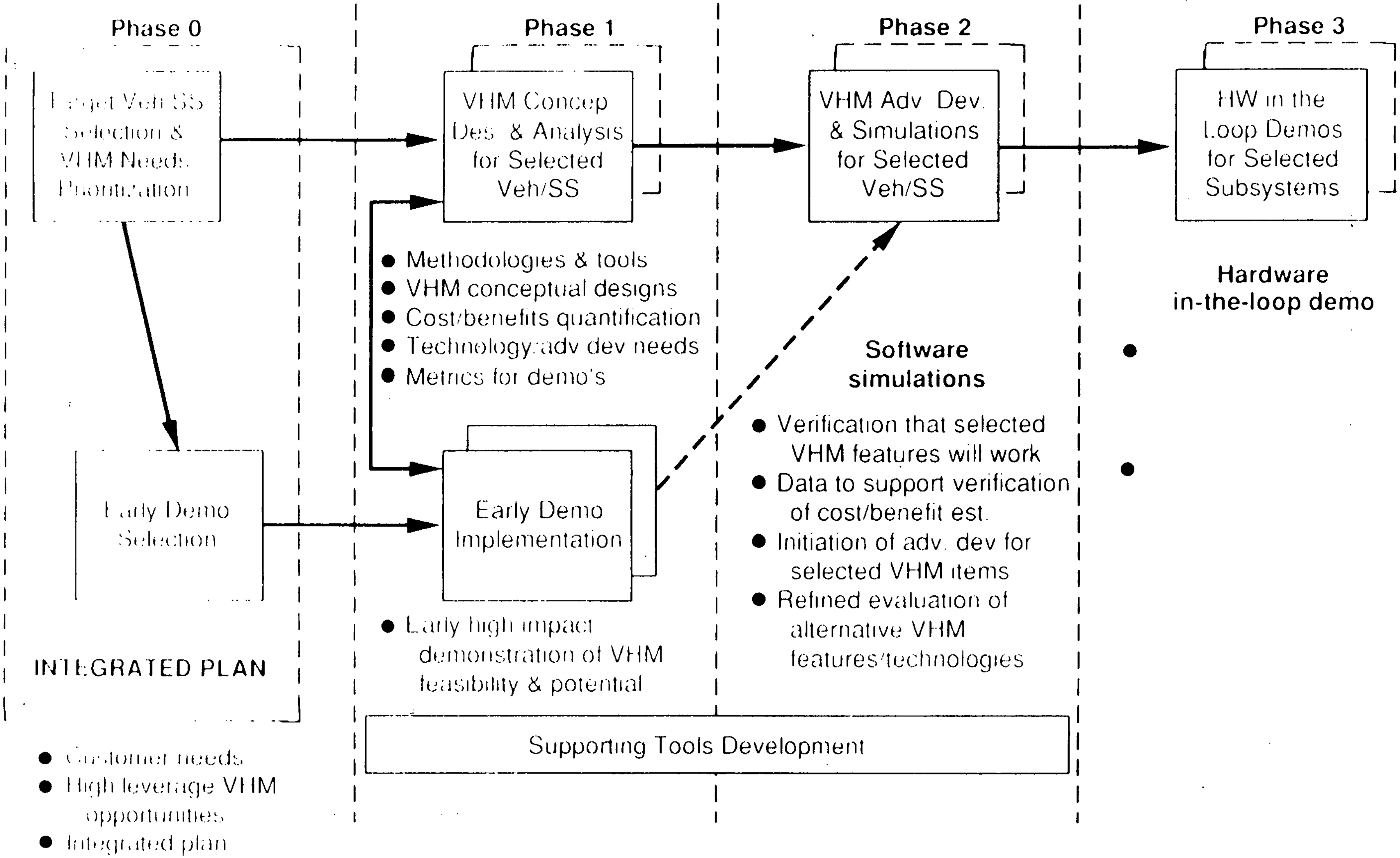
DEMONSTRATION

PRECEDING PAGE BLANK NOT FILMED

SESSION X

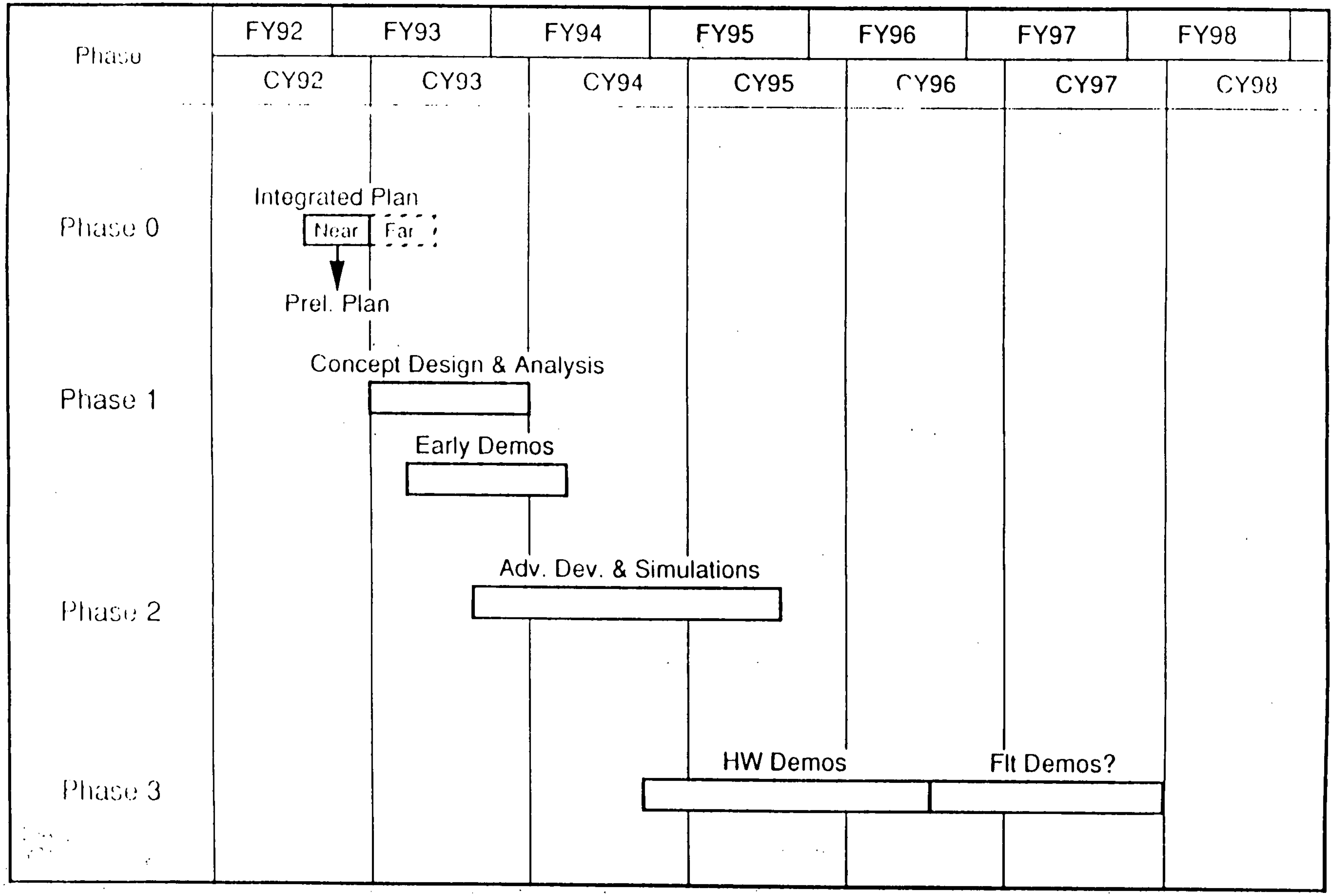
EMA FDIR AND VHM

IVHM ADVANCED DEVELOPMENT PROGRAM



VHM Development Plan

Schedule



6/30/92
1-2257-2-271

TASK PRIORITY
PHASE 0

TOP PRIORITY	TARGETS SUPPORTED
Real time engine diagnostics	ELV, STS
Leak detection	ELV, STS
IVHM Architecture	ELV, STS
Ground processing Integration	STS
IVHM for EMA	ELV, STS
OMS/RCS	STS
IVHM Cost/Payback analysis*	STS

DESIRABLE

- Post flight/test data analysis for engines
- IVHM for mission operations
- Automated Inspection techniques for engines
- Flight/ground test plume spectroscopy
- Laser pyros
- SSF Fault Management system
- Hybrid Reliability/fault tolerance/cost tool

Application required for all demos

EMA Health Management Using Smart Sensors

NASA Electrical Actuation Technology Workshop

Honeywell Systems & Research Center

Jeff Schoess

1 October 1992

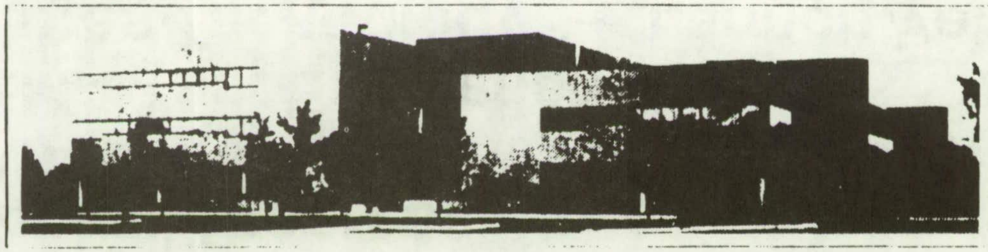
EMA Health
Management Agenda

- Role of Health Management -- A Honeywell Perspective
- Launch Vehicle Management Approach
    * NLS Avionics Configuration
    * Vehicle Integration Logic Flow
    * Functionality Definition
- Key Building Block Technology --- Smart Sensors
- Recent Technical Progress
    * 2 HP EMA Motor Current Health Monitoring
    * 28 HP EMA Test Evaluation
- Smart Structures Technology --- Launch Vehicle Application
- Summary

Systems and Research Center

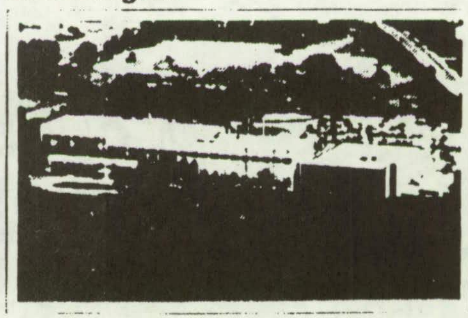
Mission: Applied research for Honeywell's space and aviation business

Minneapolis



Phoenix

Bloomington



Resources

460 people
280 engineers/scientists/technicians

\$45M Total Funding
\$32M Contracts
\$ 9M IR&D
\$ 4M Divisions

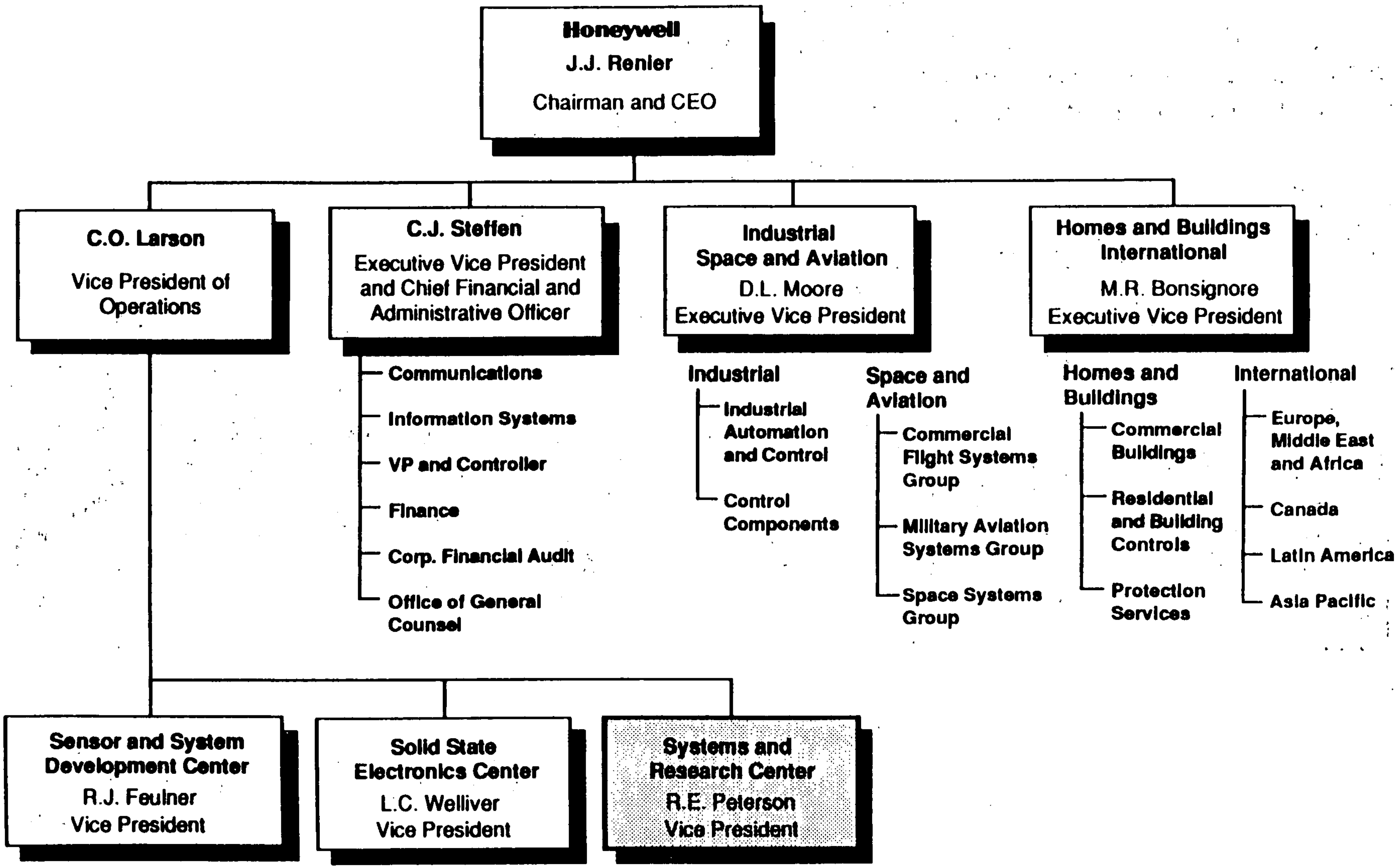
Technologies

Sensors
Microsystems/Circuits
Signal Processing
Control Systems
Displays
Computer Systems

Honeywell

C910082 1c 7/91

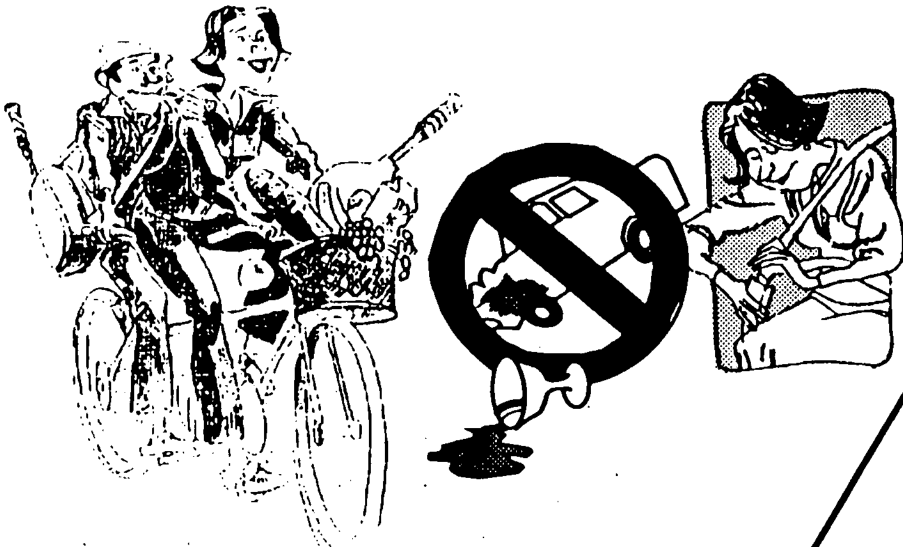
Honeywell Inc.

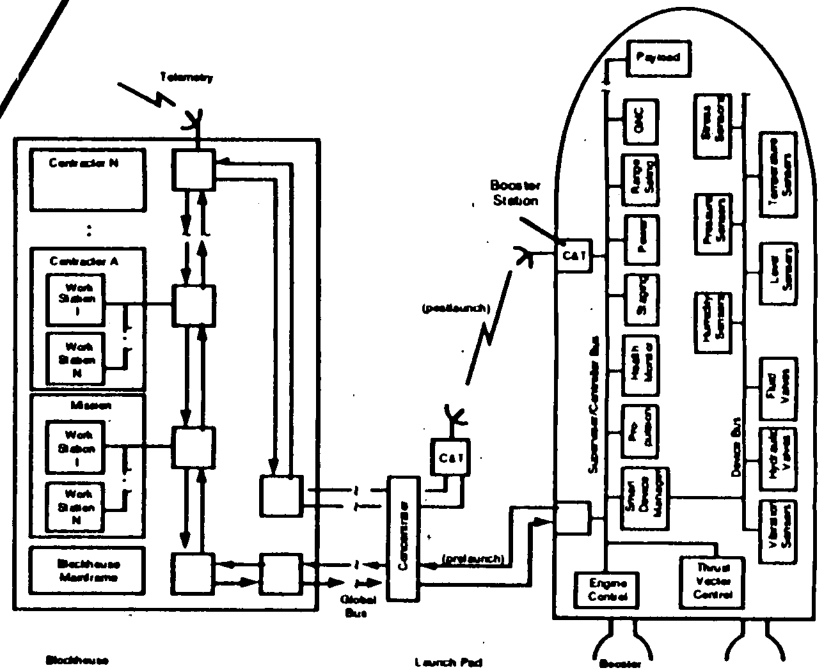


Health Management Philosophy

Human

Health management is more than not being sick—it's a way of life aimed at reducing your risk of serious illness





Launch System

Health management is more than determining that a system is working nominally—it's a system design aimed at reducing the risk of system- and mission-threatening failures

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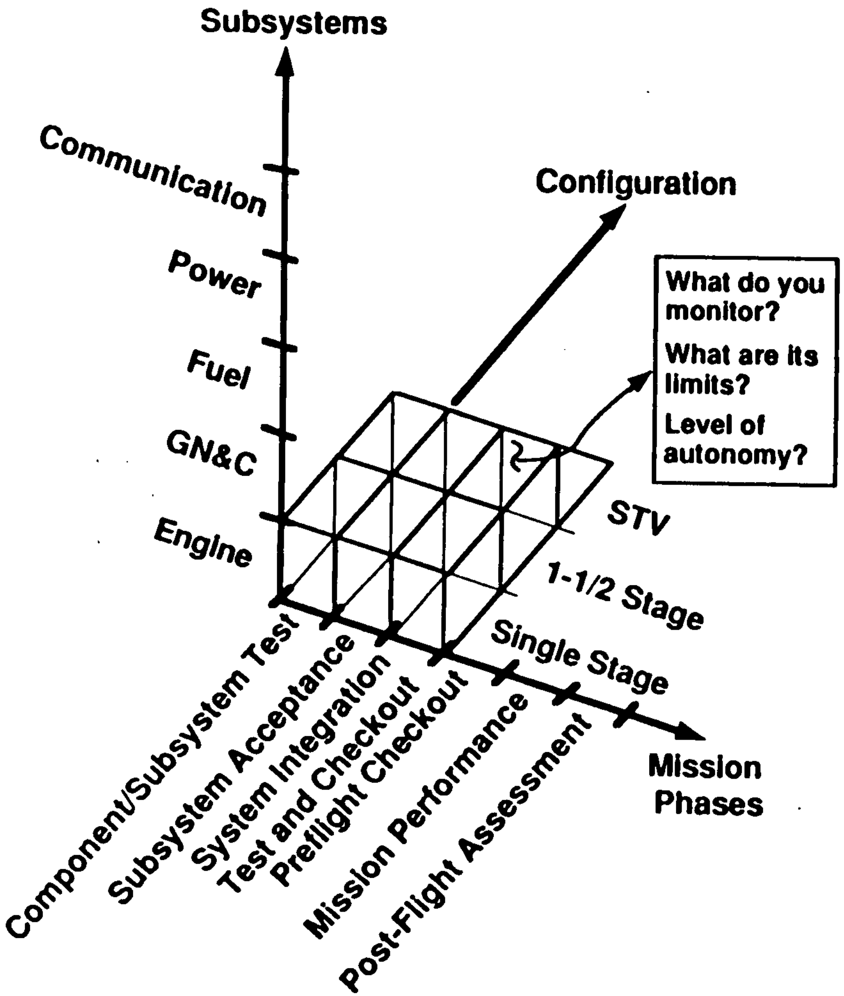
Honeywell Perspective—A Systems View



A health management system—

- Monitors, evaluates and diagnoses system health; it integrates the following elements:
  - Nominal system status/configuration/nominal operation/checkout data
  - On-line condition and safety monitoring
  - Predictive and preventive diagnosis
  - Fault detection, isolation, recovery (including BIT)
  - Explanation and recommendation facility
  - Integrated maintenance database
- Is part of an integrated launch system controls architecture that provides life-extending control to maintain assets and reduce replacement costs, as required

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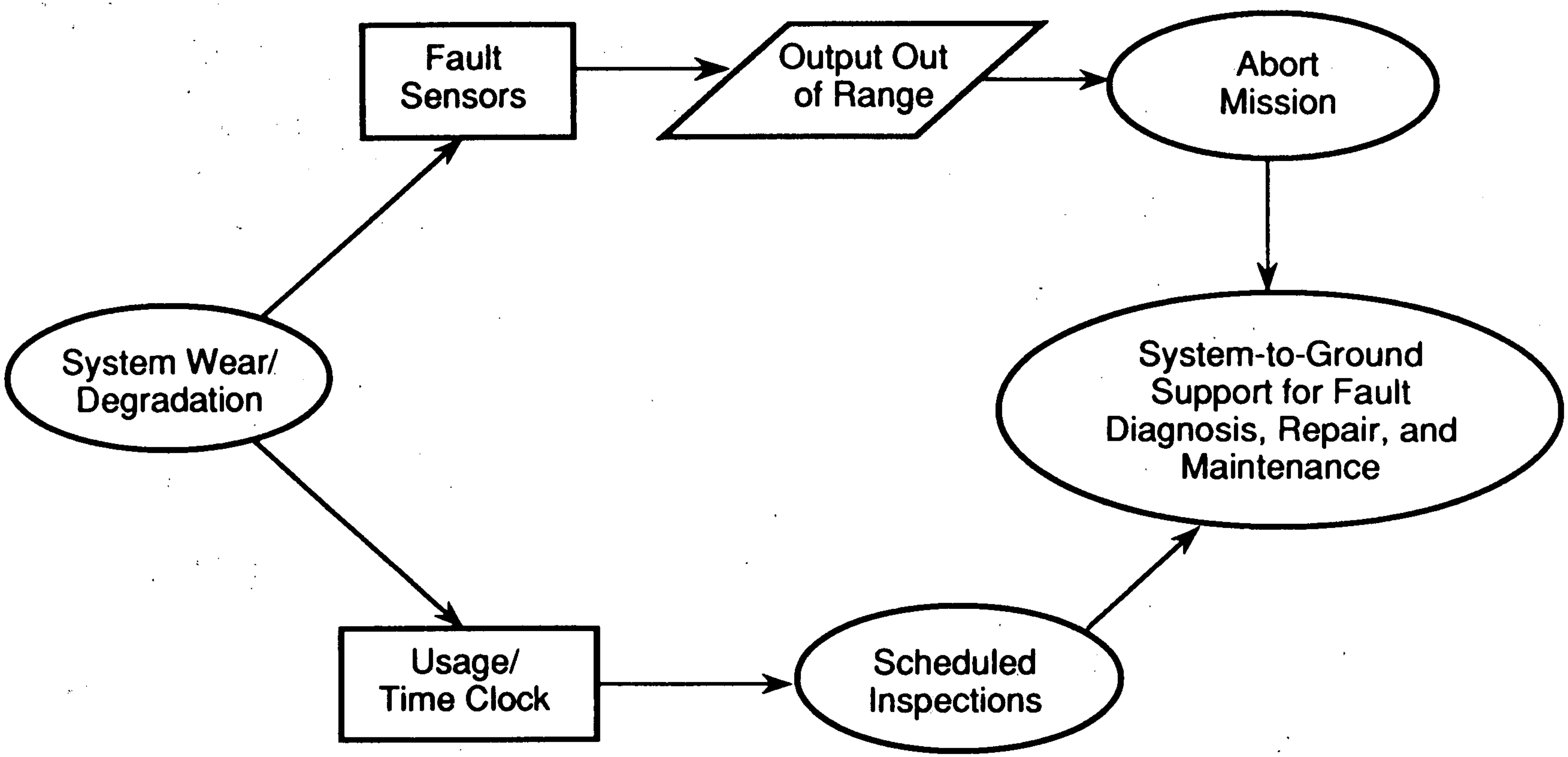
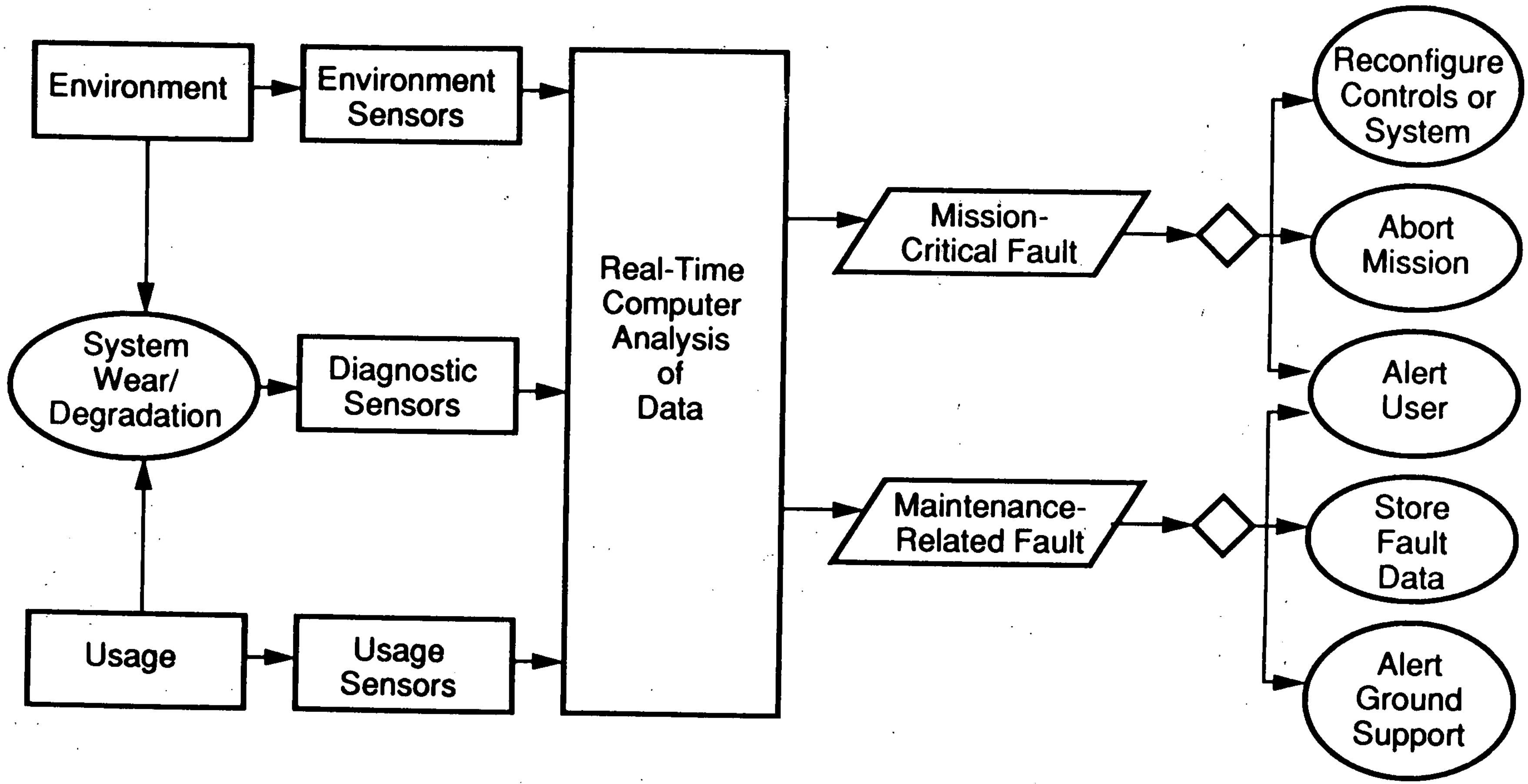
Health-Monitoring Systems

The Present Situation

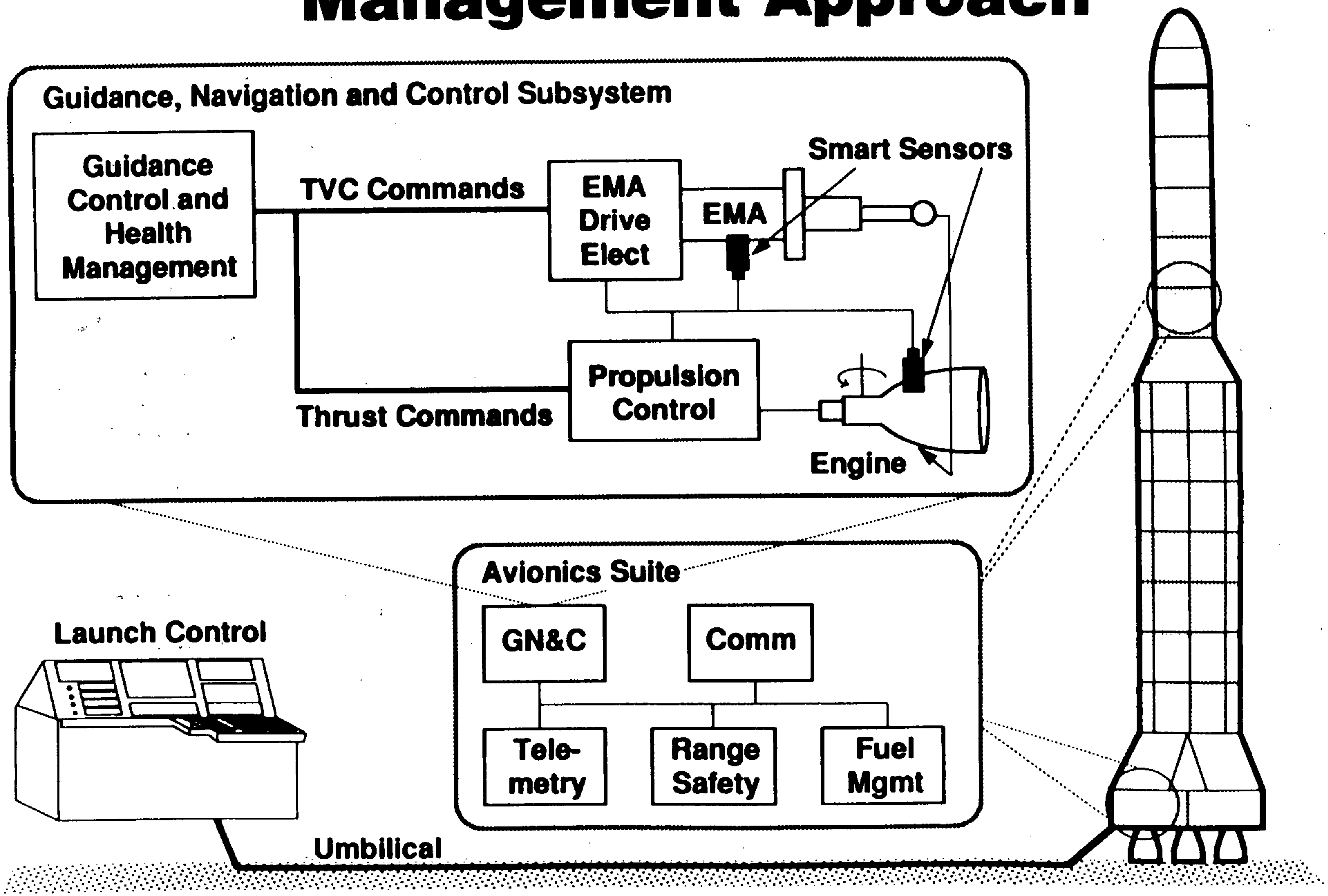


Health-Monitoring Systems

The Future



Advanced Launch System Health Management Approach



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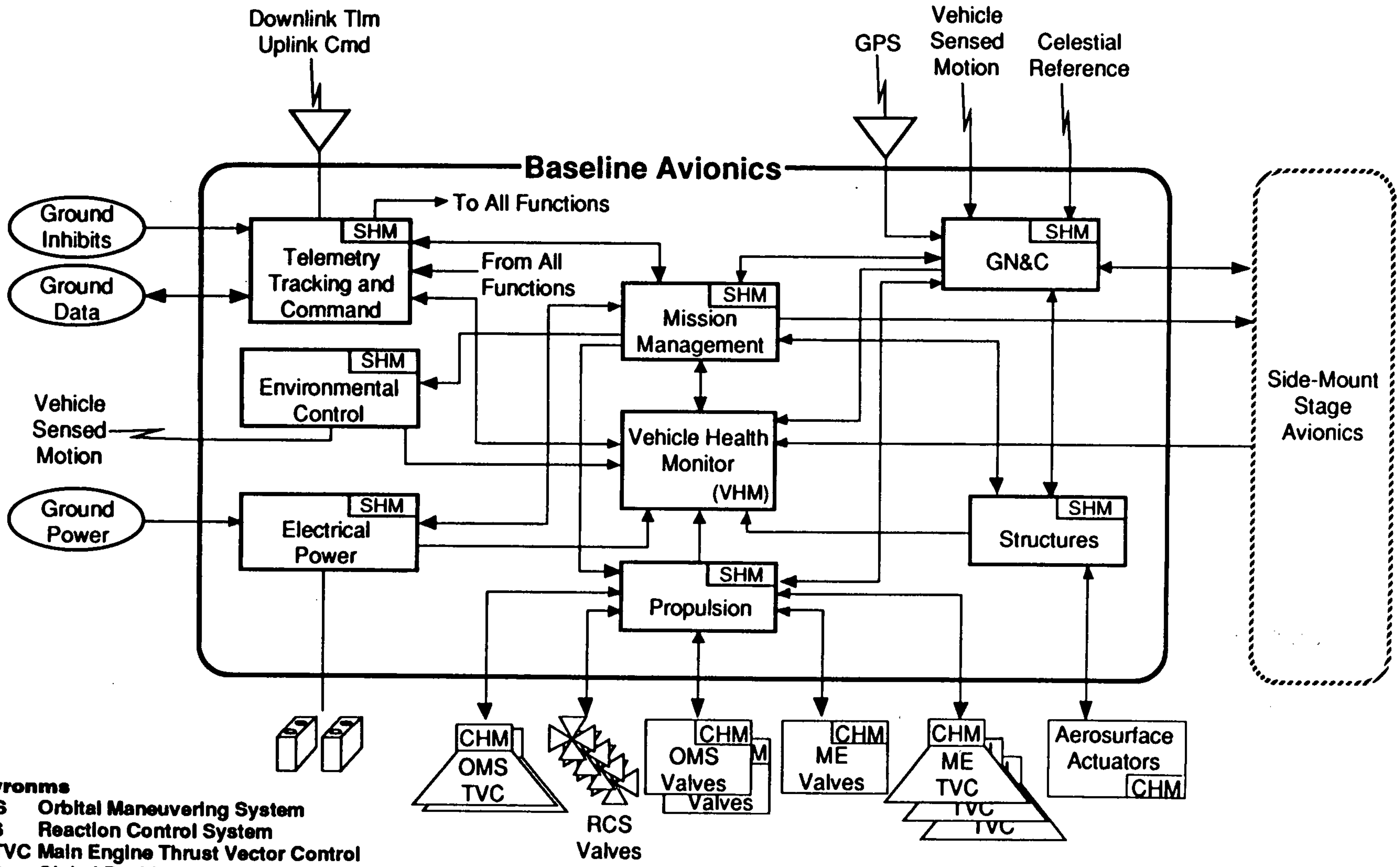
HLV Baseline Avionics Configuration



Acyronms
OMS Orbital Maneuvering System
RCS Reaction Control System
METVC Main Engine Thrust Vector Control
GPS Global Positioning System
SHM Subsystem Health Monitoring
CHM Component Health Monitoring

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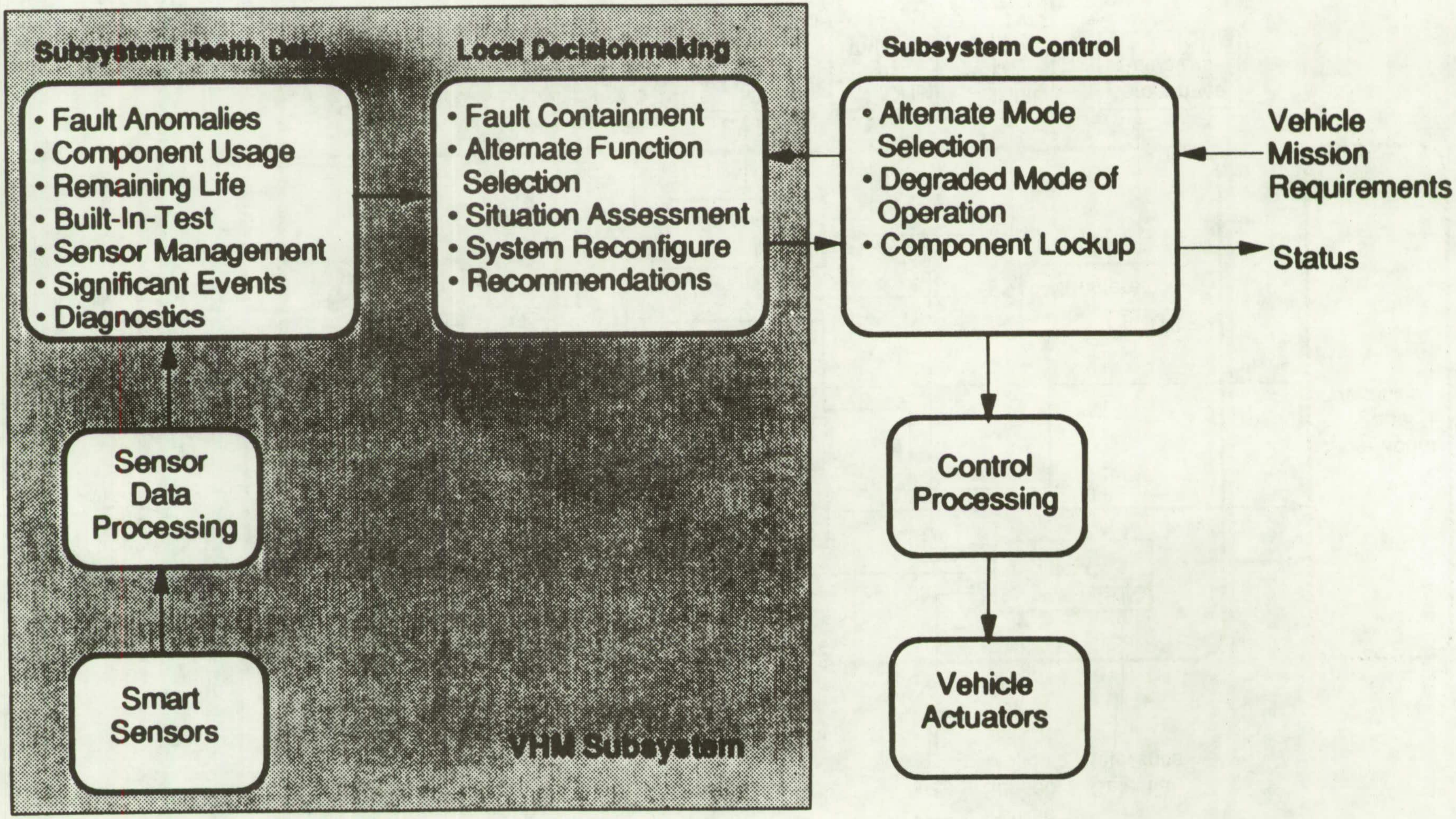
VHM Integration Logic Flow



Smart Structures Functionality Definition

Vehicle Goals

- Fault avoidance
- Reduced maintenance on schedule/demand
- Remaining life

System Goals

- Automated checkout
- Real-time monitoring
- Integrated Maintenance
- Fault prognosis/diagnosis
- Information management and control

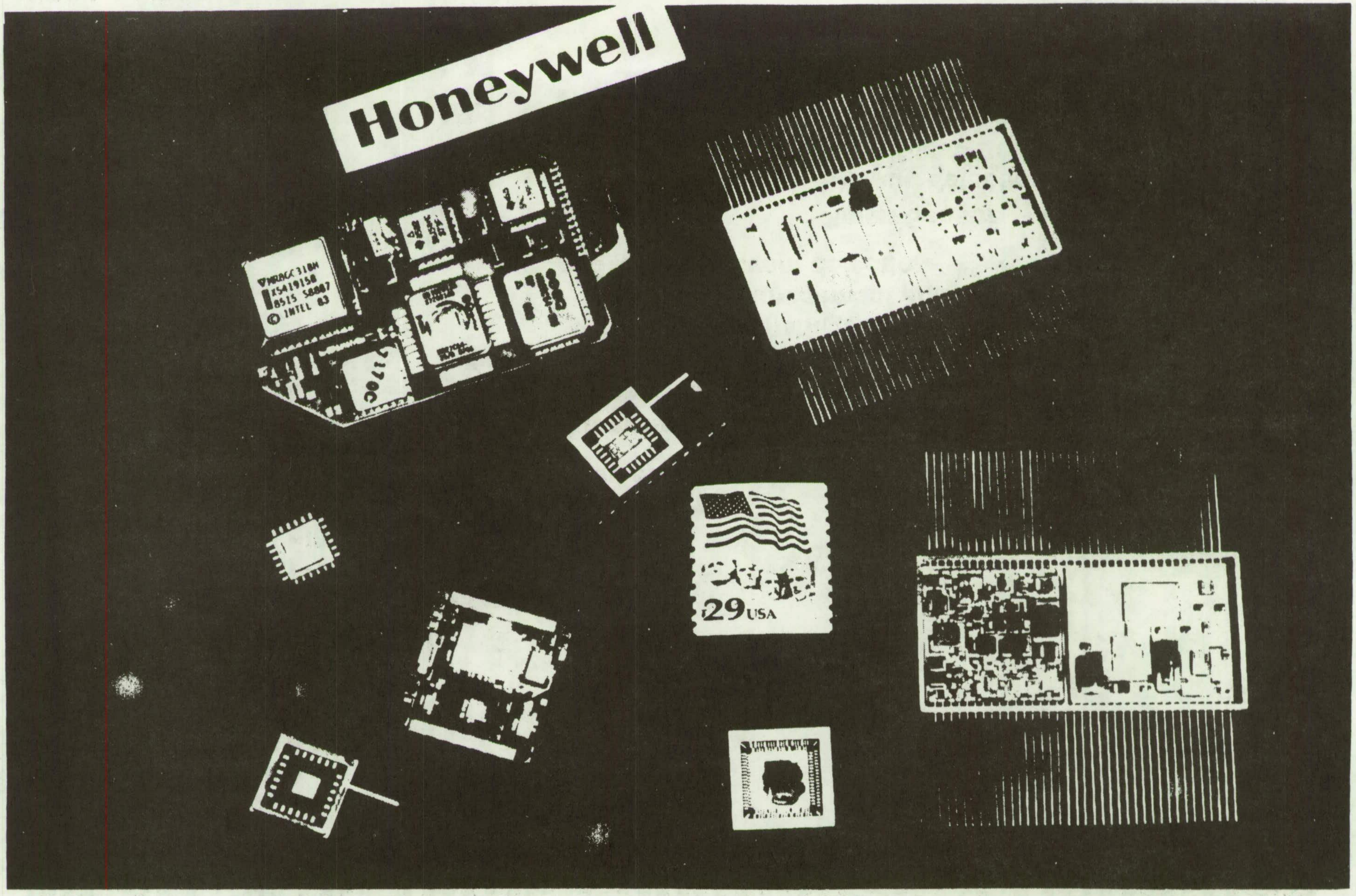
Subsystem Goals

- Resource allocation
- Fault prediction, detection, isolation
- Redundancy management
- Local data management and control
- Significant event detection

Smart Sensor

- Fault detection and isolation
- Self-test
- Local data qualification
- Time-stamping of data
- Data reasonability tests

Smart Sensor Microsystems



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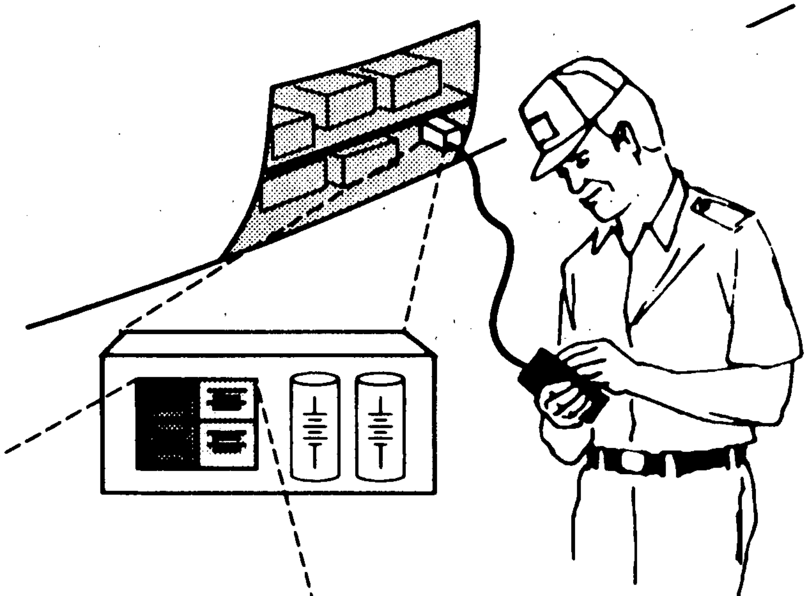
Time and Stress Measurement Device



Temperature	Data Processing and Time Keeping
Humidity	
Shock	Large Data Memory
Vibration	

Time and Stress Measurement Device (TSMD)

A TSMD is a miniature electronic device or compcnent which senses environmental stress parameters that can cause failures in electronic systems. These parameters are

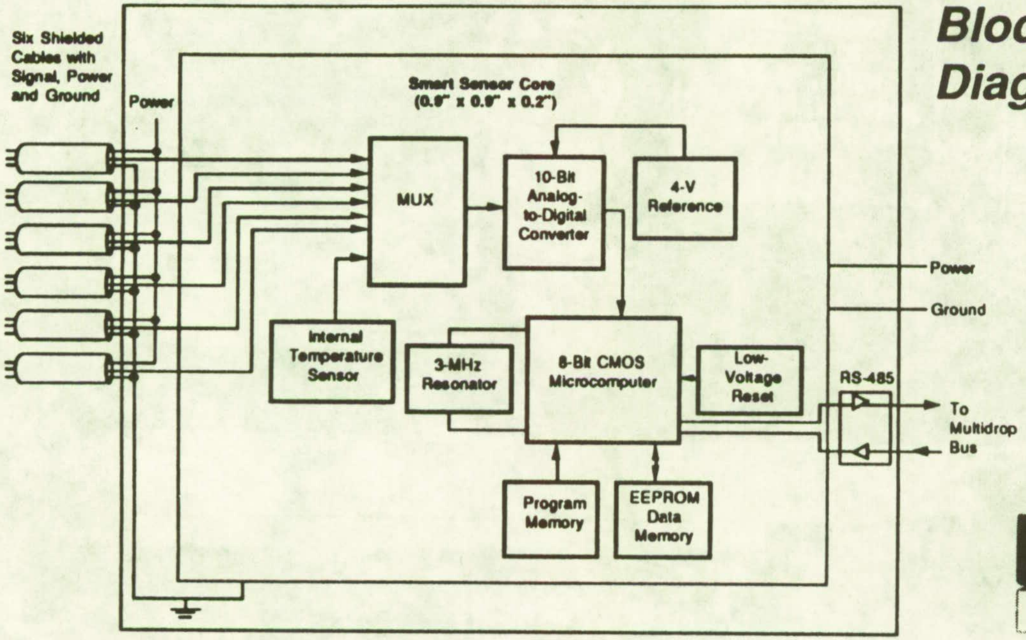
- Vibration
- Shock
- Temperature
- DC voltage
- Voltage transients

TSMD processes the stress data and stores it in nonvolatile memory

The TSMD is designed to accumulate stress data for months or years of use

A real-time reference maintained by the TSMD can show the date and time of particular stress events

Smart Sensor Electronics Core



Block Diagram

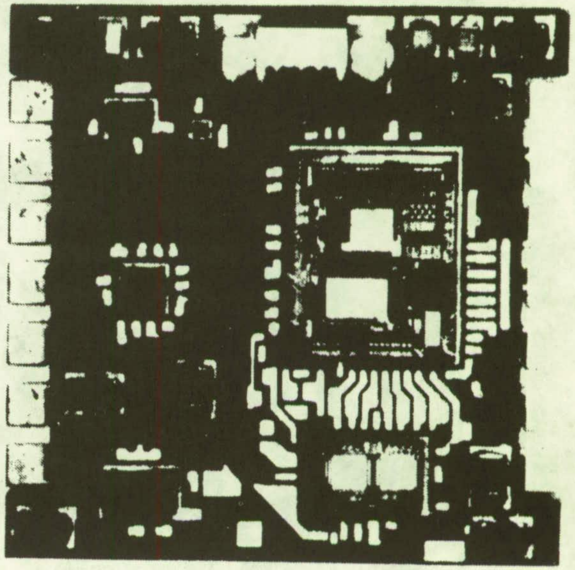
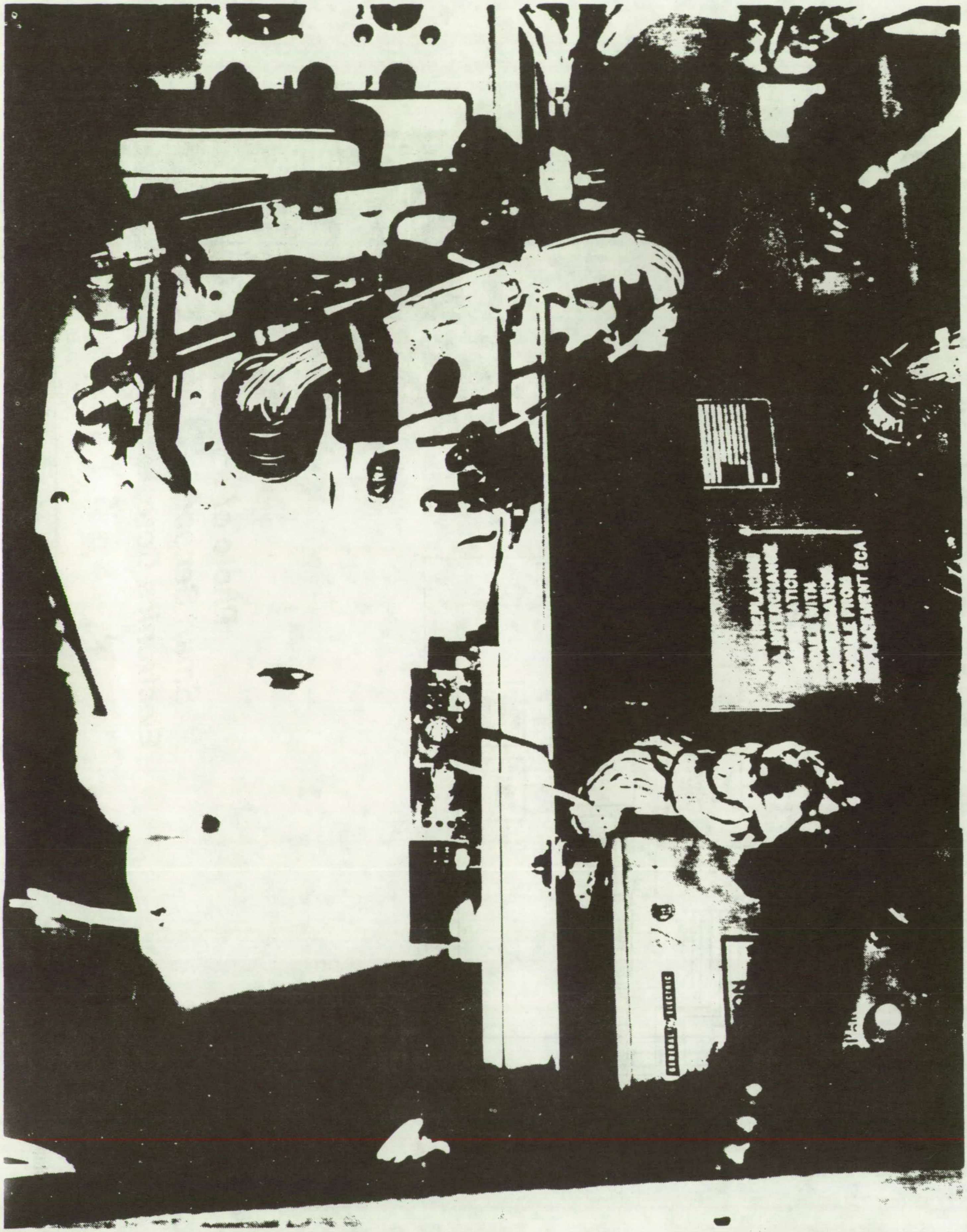


Photo of Smart Sensor Electronics Core



Two-Horsepower Electromechanical Actuator

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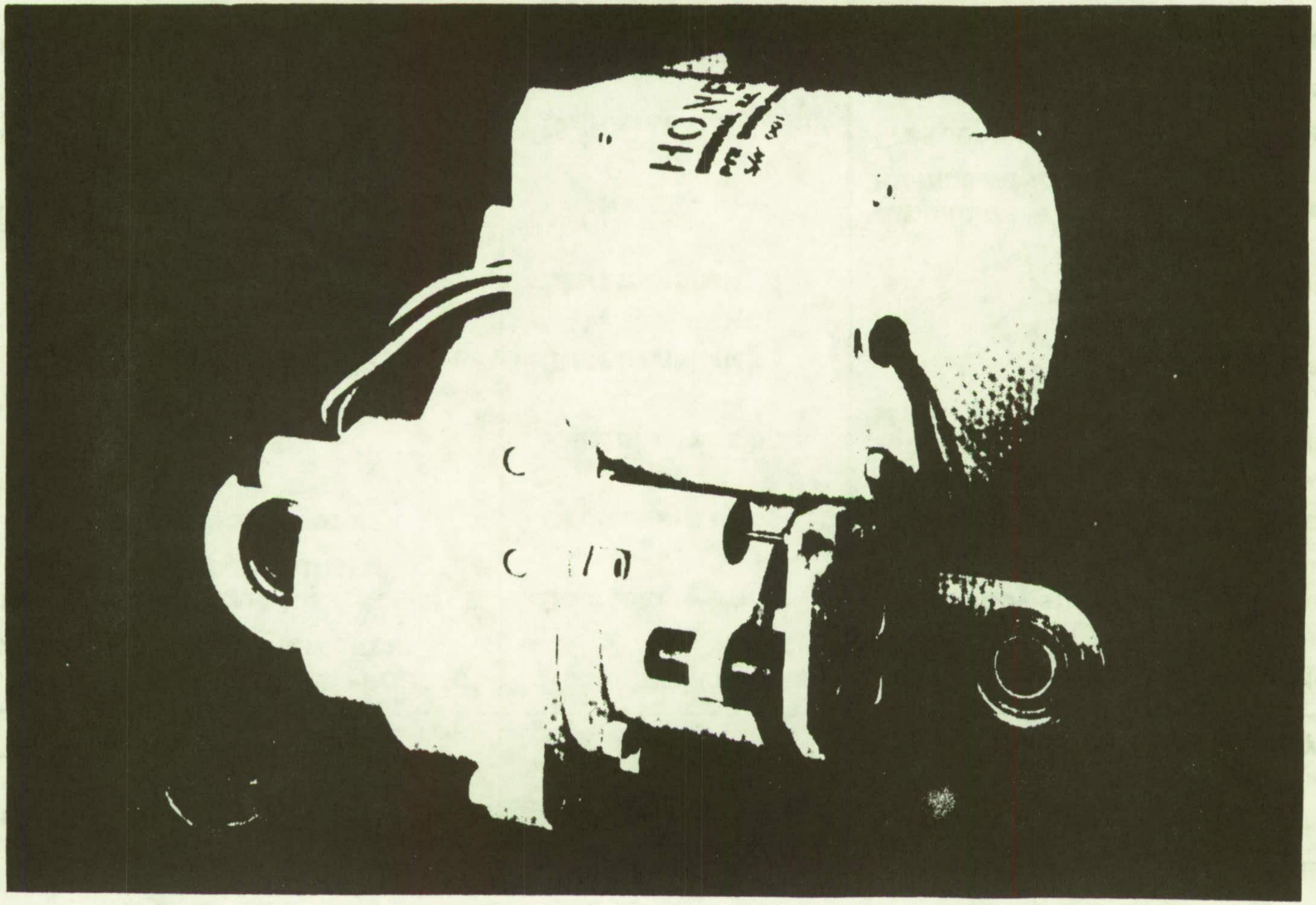
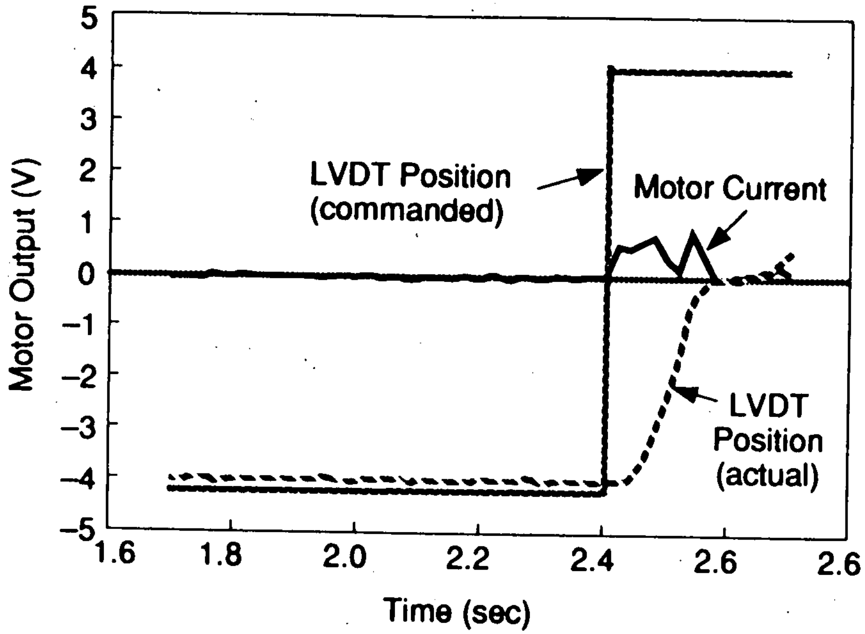
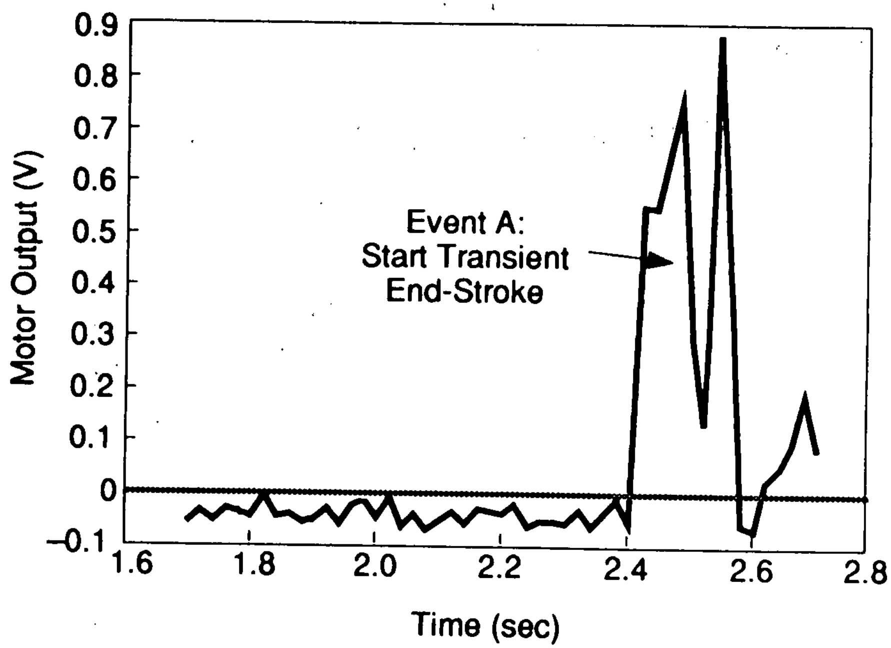


Motor Current Health Assessment Matrix

Motor Failure Modes \ Signature Analysis	Failure Mode Effects	Motor Current Signature: Time Domain	Motor Current Signature: Frequency Domain	Type of Failure
1 Loose/Corroded Electrical Connector	Loss of power due to open/short circuit	Random transients	–	Degraded
2 Motor Winding Failure	Torque loss, power supply transient	Decreasing trend	Frequency shift	Catastrophic
3 Motor Gear Disengagement	Loss of motor actuation	Decreasing trend	Amplitude increase/decrease	Catastrophic
4 Motor Gear Tooth Breakage	Gear wear	Random transients	Amplitude frequency shift	Degraded
5 Lubrication Failure	Motor gear lockup	Start transient	–	Catastrophic
6 Gear Shaft Stiffness	Shaft wear	Start transient	–	Degraded
7 Motor Bearing Failure	Bearing race wear, ball bearing wear	–	Amplitude increase/decrease	Catastrophic
8 Gear Interface Slop	Gear wear	Start/stop transients	Frequency shift	Degraded
9 Motor Speed Slip	Intermittent operation	–	Frequency shift	Degraded
10 Linear Actuator Stiction	Actuator wear	Start/stop transients	–	Degraded
11 Actuator Obstructions	Burn-out motor mechanisms	Increasing trend	Frequency shift	Catastrophic

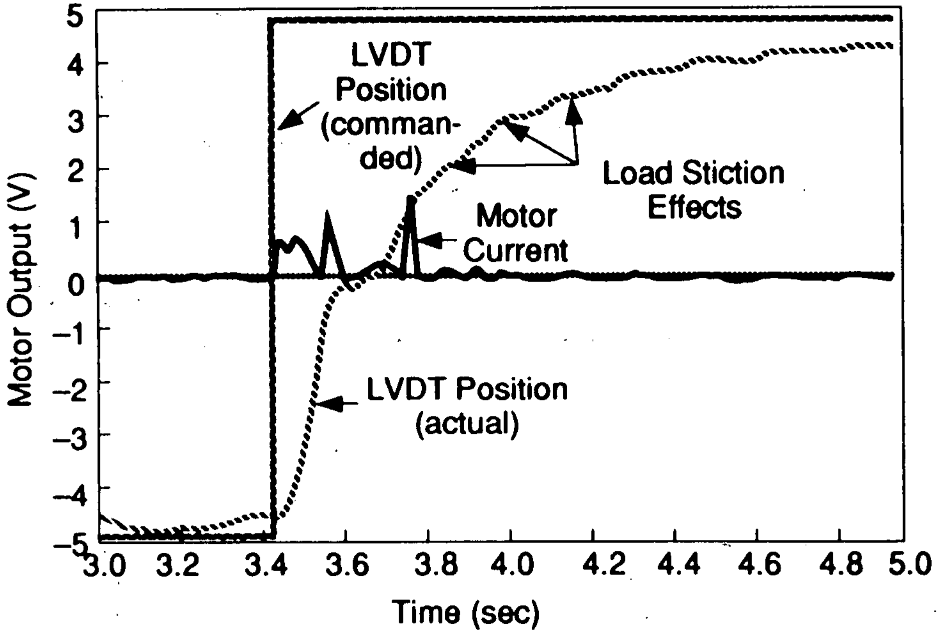
EMA Test 1: Loose Actuator Bearing Anomaly

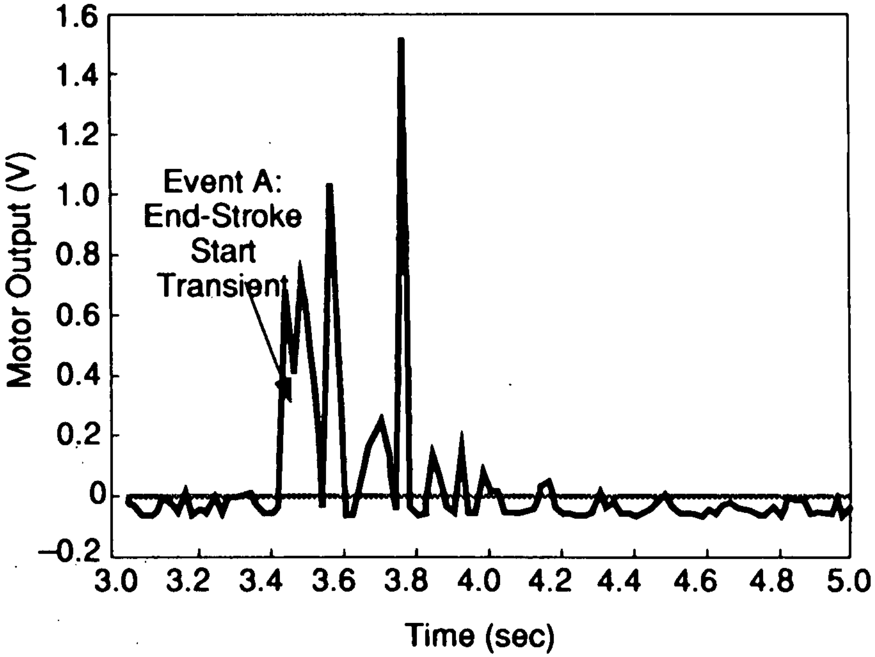




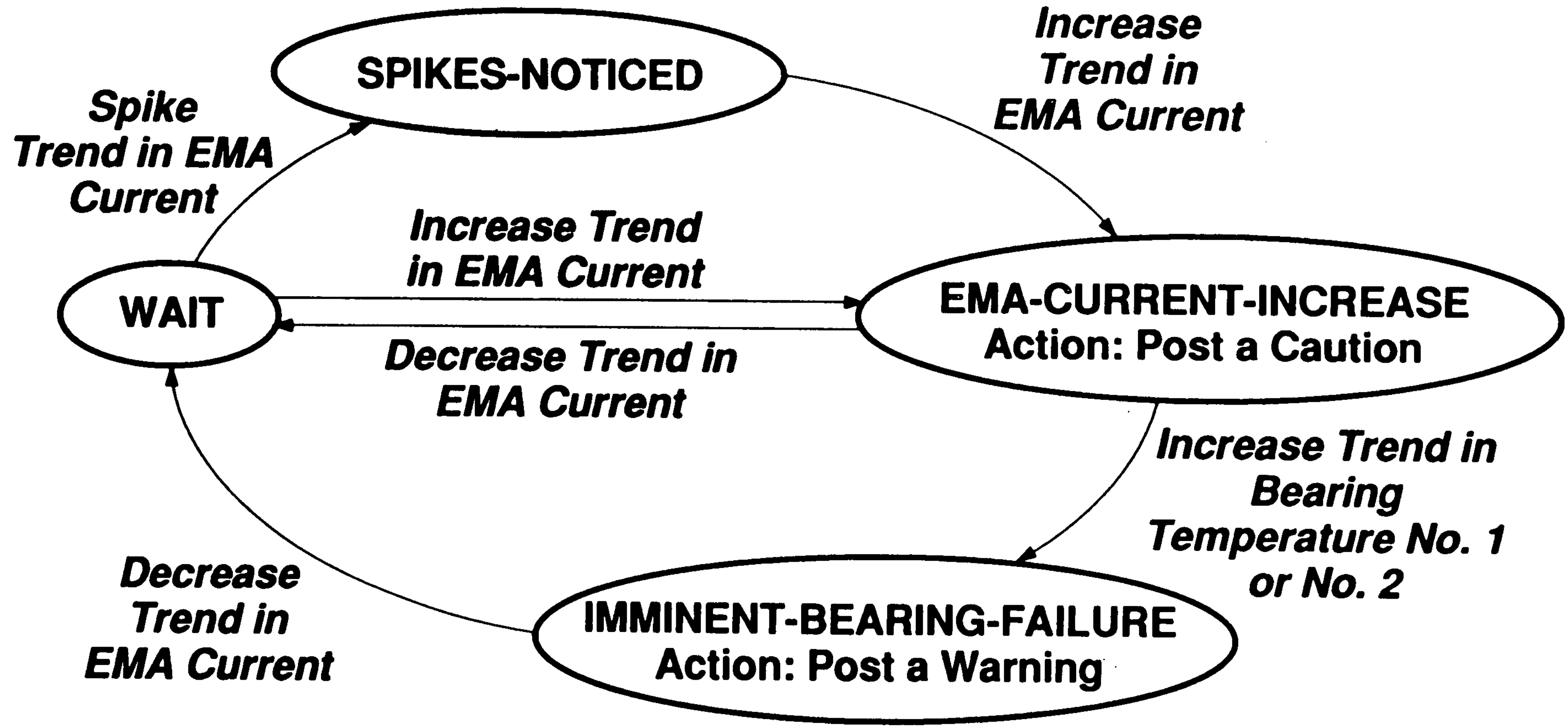
Detailed View of Motor Current

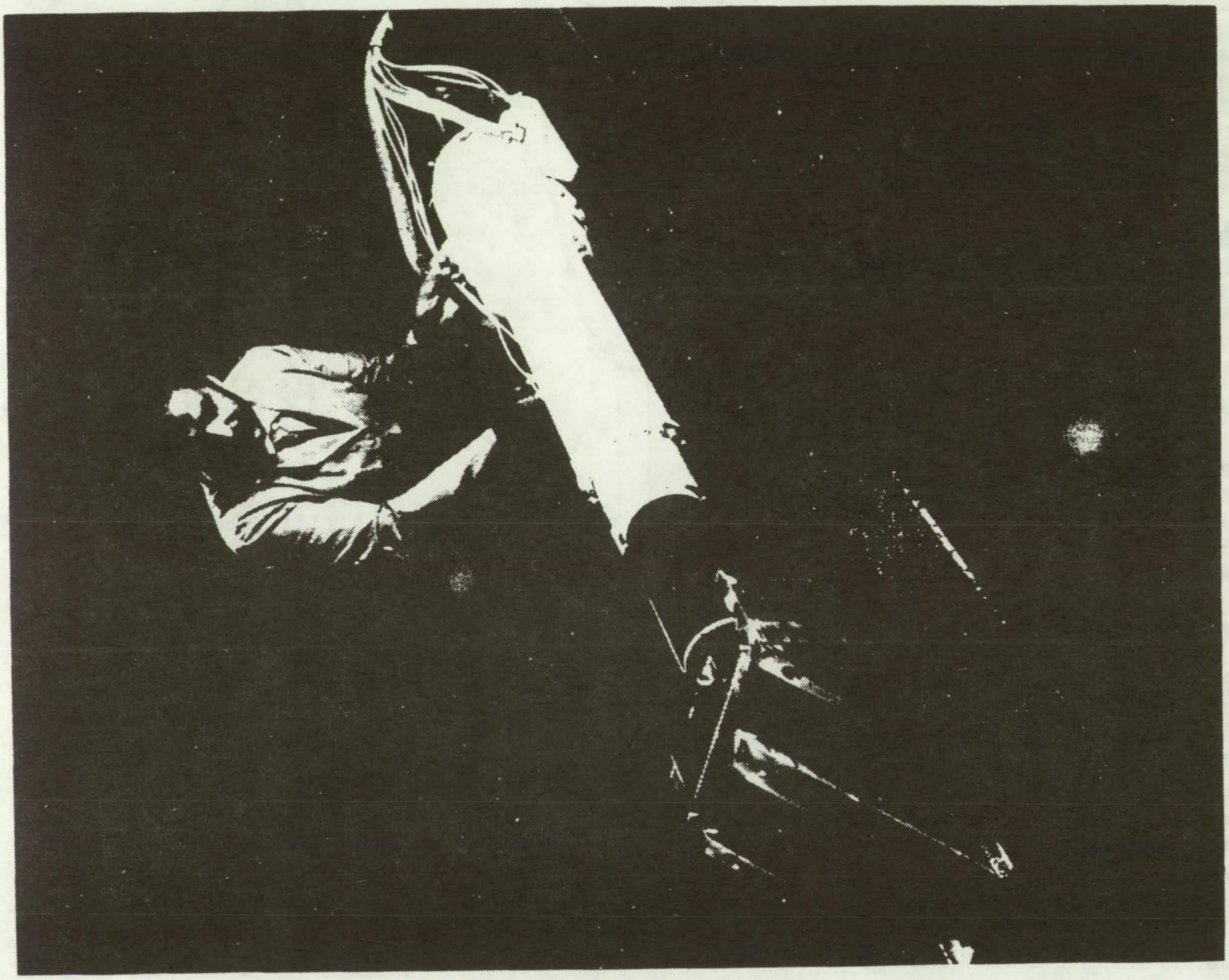
EMA Test 2: Tightened Actuator Bearing Characteristics





EMA Bearing Wear Failure Prediction Example





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EMA Motor Winding Failure

Priority 2

Test Objective—to detect a motor winding failure due to emulated failure of winding conductor or motor slot insulation

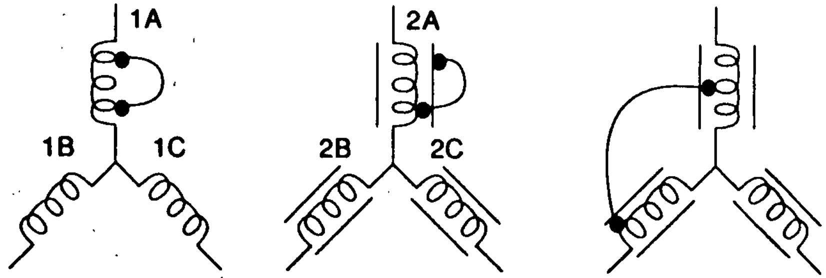
EMA Failure Mode—a failure of the EMA motor winding assembly; three possible failure scenarios:

- Normal to open circuit due to winding conductor failure (vibration, fatigue) or mechanical disconnect
- Normal to short circuit due to insulation breakdown, wear
  Three types of shorts
  1. Turn-to-turn short
  2. Short-to-stator frame
  3. Winding-to-winding short
- Short to open circuit due to excessive conductor heating

FMEA Characterization Procedure

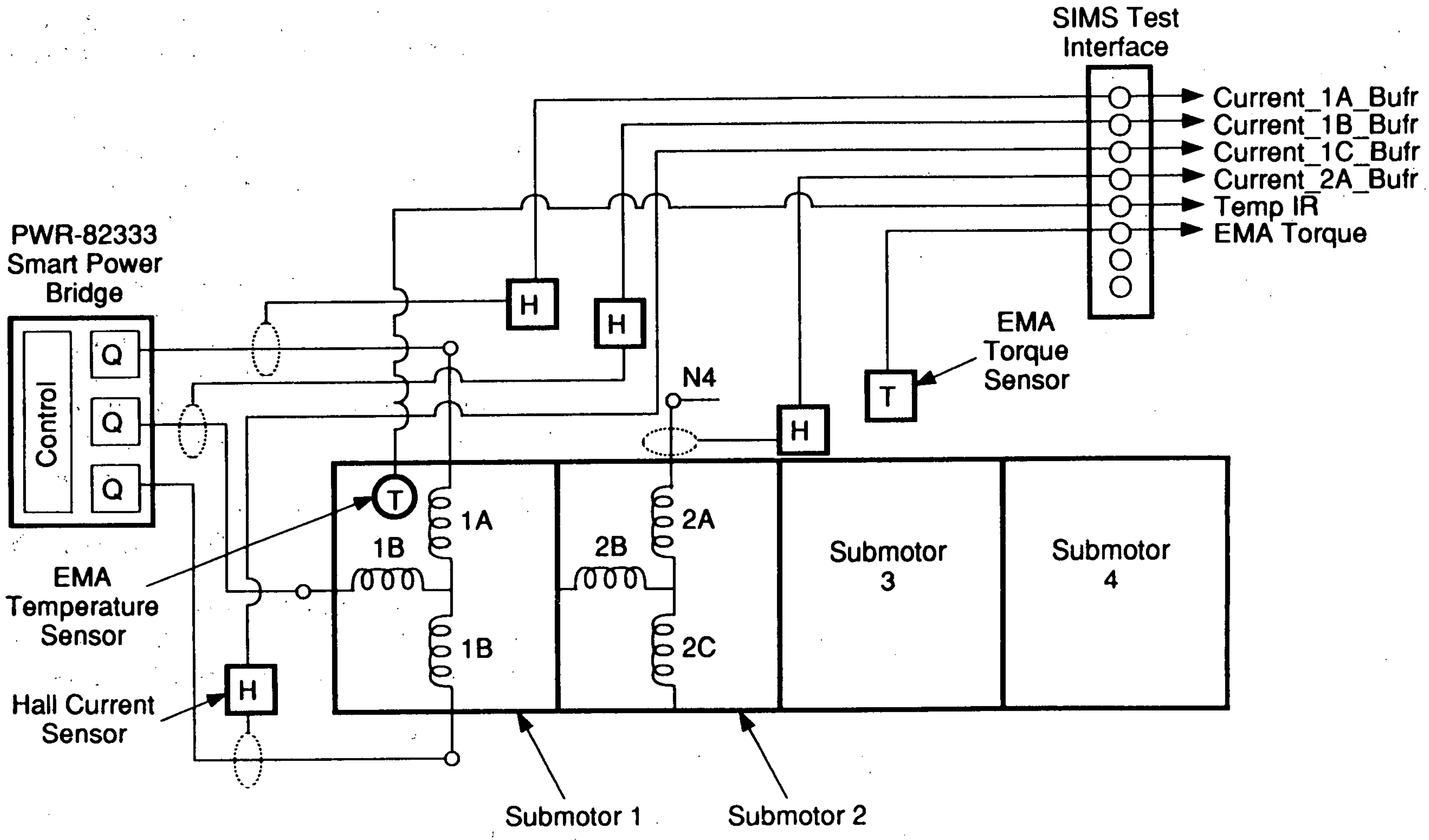
1. Attach load to EMA actuator and command to move attached load at frequency of 0.5 Hz
2. Perform test sequence in table and record results

Turn-to-Turn Short | *Short-to-Stator Frame* | *Winding-to-Winding Short*

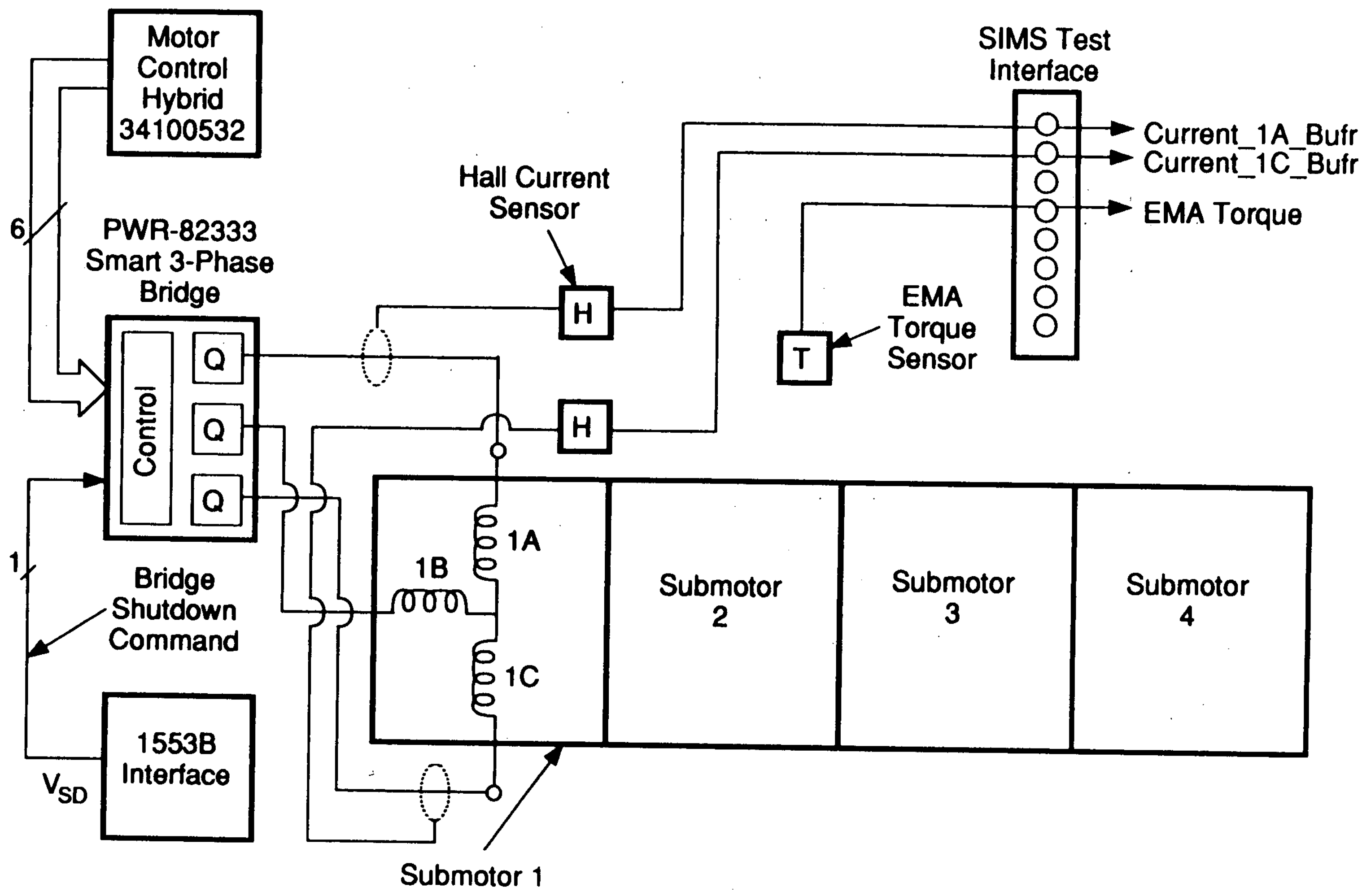


Type of Failure Mode	Characterization	Circuit Designation	Measured Parameters	Expected Results
Short Circuit	Short-to-station (local test)	1A to ground	• Current_1A • Torque • Temp_IR	• Significant torque loss (1/2 of submotor)
	Winding-to-winding (local test)	1A to 1B	• Current_1A, 1B • Torque • Temp_IR	• Torque loss (2/3 of submotor) • Torque drag effect
	Submotor-to-submotor (global test)	1A to 2A	• Current_1A, 2A • Torque • Temp_IR	• Increased equivalent inductive load • Torque ripple effect • Ground current fault
Open Circuit	Winding node 1A	—	• Current_1A • Torque	• Torque loss (torque ripple effect)

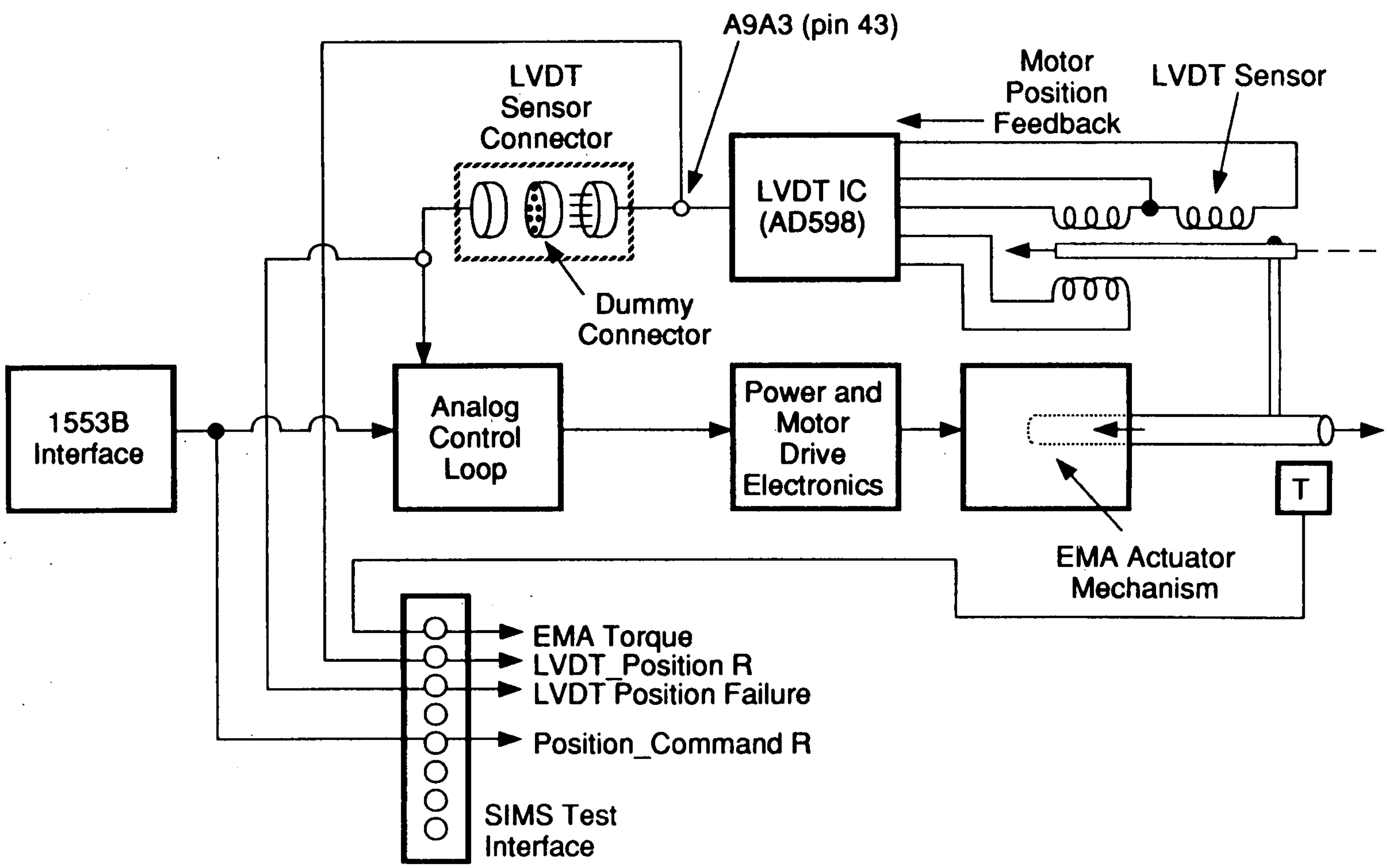
Motor Winding Failure Schematic



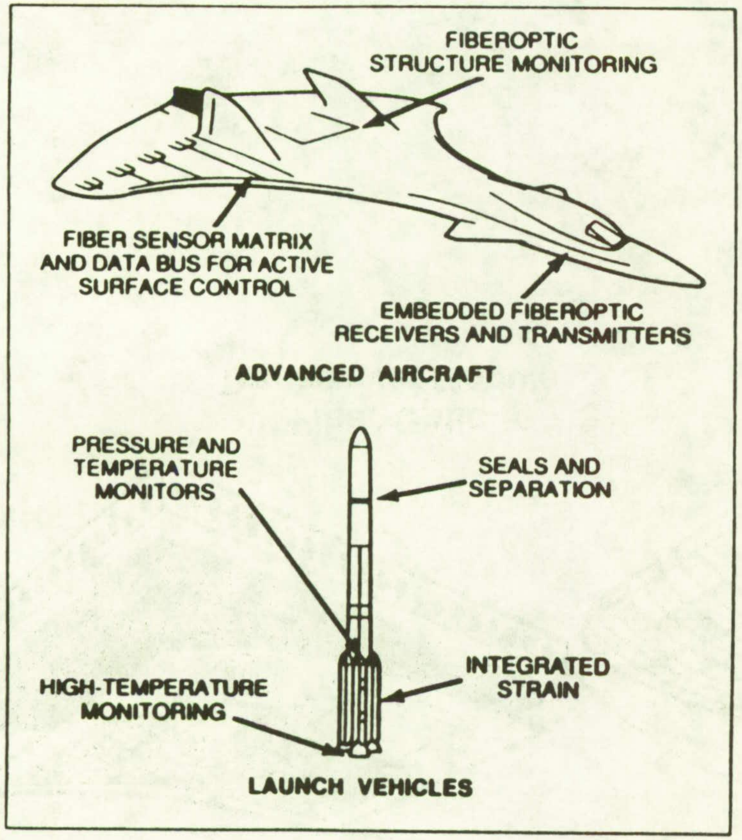
Power Transistor Failure Schematic

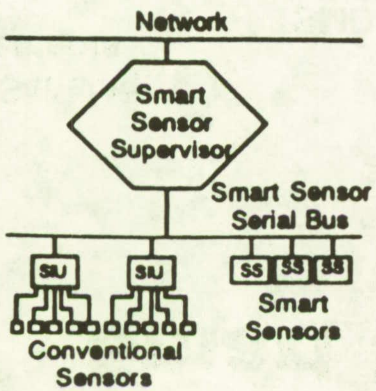


Loose Connector Failure Schematic



Signal and Data Acquisition Systems





Objective:

Smart Sensor Networks for Vehicle Health Monitoring

Features:

Detect and Isolate Potential Fault Anomalies via Built In Test (BIT)

Evaluate Subsystem Health Status/ Recommend Corrective Action

Applications

Structural Monitoring of Aging Aircraft

Launch Vehicle Integrity Assessment

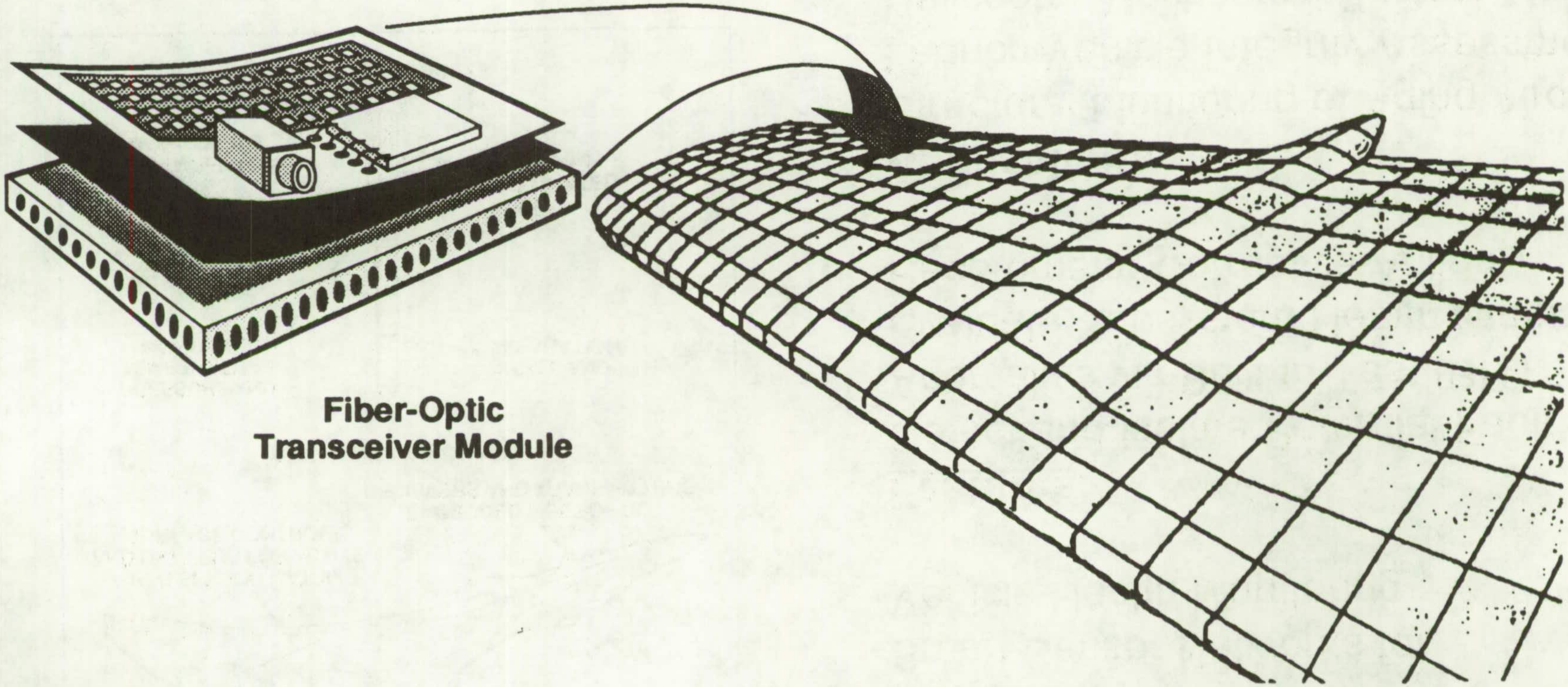
Helicopter Mechanical System Monitoring

Space Platform Damping and Pointing

Nuclear Reactor Monitoring

Smart Structure Concept

Skin-Deep, Smart Sensors May Blanket Future Aircraft to Detect and Isolate Internal Structural Damage Characteristics

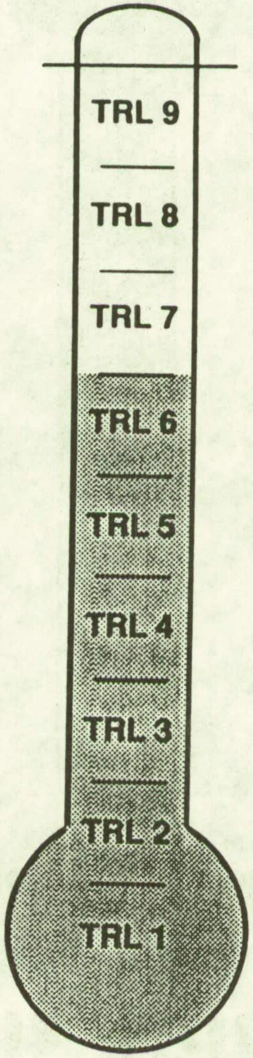


Smart Sensors

Lessons Learned

- Reduces wire weight significantly
- Supports multisensor commonality and modularity
- Supports significant local information processing, communication, and integration
- Permits low-power implementations
- Permits BIT at low system levels
- Allows I/O interface standardization
- Permits multiple applications to be met by one package (e.g., through reranging)
- Supports fault tolerance through redundant transducer packaging

Technology Readiness Level



Needs

- Selection of applications
- Selection of packaging approach
- Development of high-temperature components
- Selection of standards

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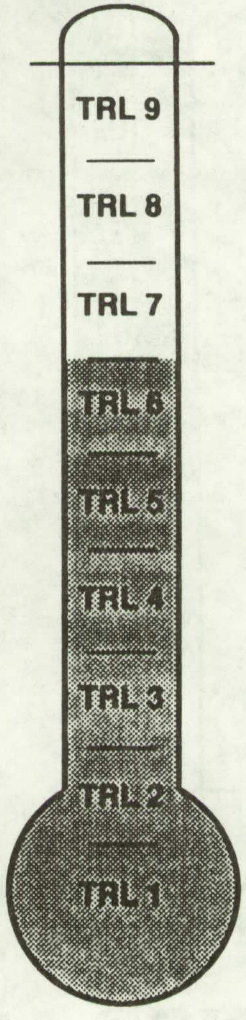
Maintenance Diagnostics and Intelligent Algorithms

Lessons Learned

- Health monitoring algorithms do not require dedicated health monitoring sensors
- Predictive diagnostic algorithms can be developed for specific cases for systems that have a design heritage
- Maintenance systems pay for themselves through productivity improvements
- Data filter state monitoring and trend monitoring algorithms are computationally efficient
- Development requires close cooperation among domain experts, users, and maintenance system designers

Technology Readiness Level



Needs

- Language selection
- Verification and validation methodology development
- System-level demonstration
  - Diagnosis through maintenance aiding
  - Incorporation of technology building blocks

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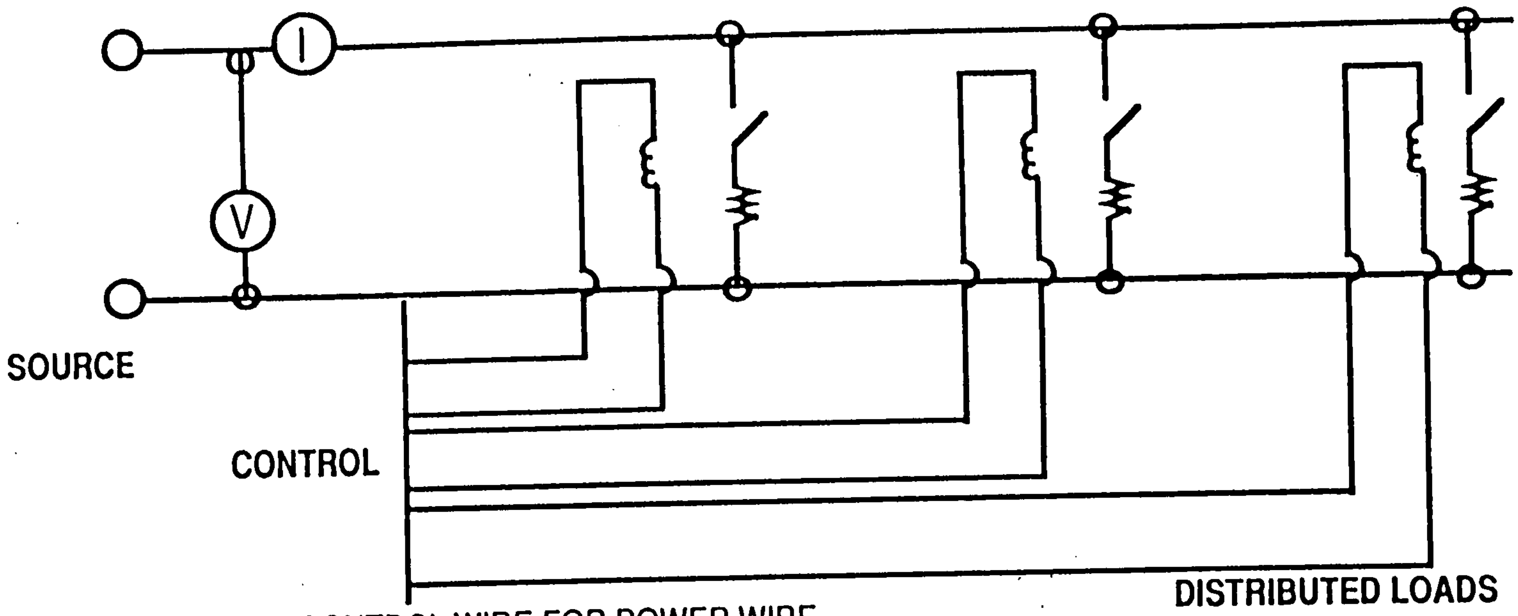
Intelligent Built-In Test for Electric Actuators

Irving Hansen
NASA Lewis Research Center
Cleveland, Ohio

DISTRIBUTED POWER/CENTRALIZED CONTROL



TRADE - CONTROL WIRE FOR POWER WIRE
ATTEMPT TO MONITOR FROM CENTRAL MEASUREMENTS
UTILITY - STATE ESTIMATION ROUTINES

LESSON: SPACE STATION EXPERIENCE

2^{200} COMBINATIONS - 1.5 MILLION LINES OF CODE WHEN ABANDONED

LESSON: THREE MILE ISLAND - SENSED THAT COMMAND WAS SENT NOT THAT VALVE HAD MOVED
BROWNS FERRY - PUT POWER WIRE AND CONTROL WIRE IN SAME CONDUIT

LESSON: "DON'T LET SOFTWARE PEOPLE DESIGN YOUR POWER SYSTEM"

BUILT IN TEST

NON INTRUSIVE - ("FIRST DO NO HARM")

SYSTEM STATUS, REDUNDANCY STATUS, PROBABLE HEALTH

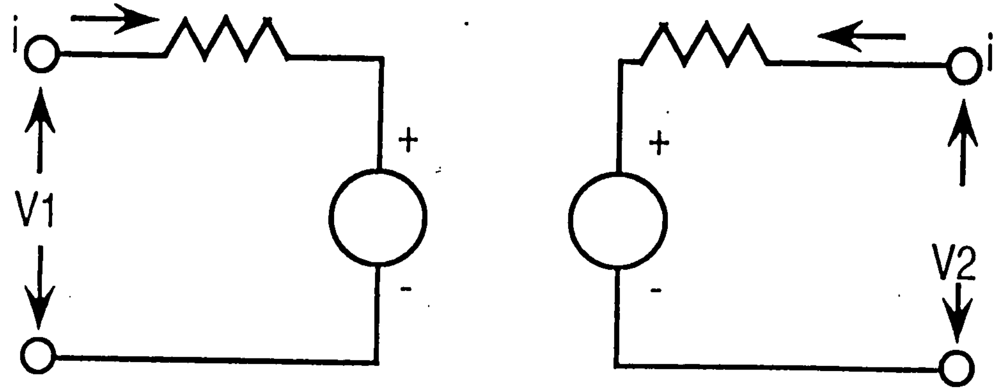
CALIBRATION AND VERIFICATION OF BIT AT EVERY CHECKOUT CONTINUOUSLY

FROM DESIGN TO DEPLOYMENT

(e.g. TESTBED, ACCEPTANCE, QUALITY TEST, PREFLIGHT)

RAPID RESPONSE, HIGH PROBABILITY OF CORRECT DECISION

SYSTEM ELEMENTS MODELED AS TWO PORT, FOUR TERMINAL NETWORKS



INPUT PARAMETER
OUTPARAMETER
FORWARD GAIN
REVERSE GAIN

} SMALL SIGNAL MODELS

(TOP DOWN) - SYSTEM REQUIREMENTS

VEHICLE HEALTH MANAGEMENT

GENERAL:

- FAILURE TOLERANCE (ROBUSTNESS e.g., FAIL OP, FAIL OP, FAIL SAFE)
  (QUAD REDUNDANCY A SOLUTION NOT A REQUIREMENT)
  - DETECTION - BUILT IN TEST
  - CONTAINMENT - DESIGN AND PROTECTION
  - ACCOMMODATION - REDUNDANCY MANAGEMENT

FUZZY LOGIC

THE LOGIC OF HANDLING FUZZY INFORMATION

ADJECTIVES - MORE, LESS, FASTER, SLOWER (FUZZY QUANTIZATION)

CRISP SETS - 0,1 PRECISE QUANTIZATION

APPLICATION TO BUILT IN TEST OF TWO PORT NETWORKS

INPUT - ERROR SIGNAL (OR COMMAND)
OUTPUT - CURRENT OR VOLTAGE } CRISP DATA
FORWARD GAIN - RATIO OF OUTPUT TO INPUT

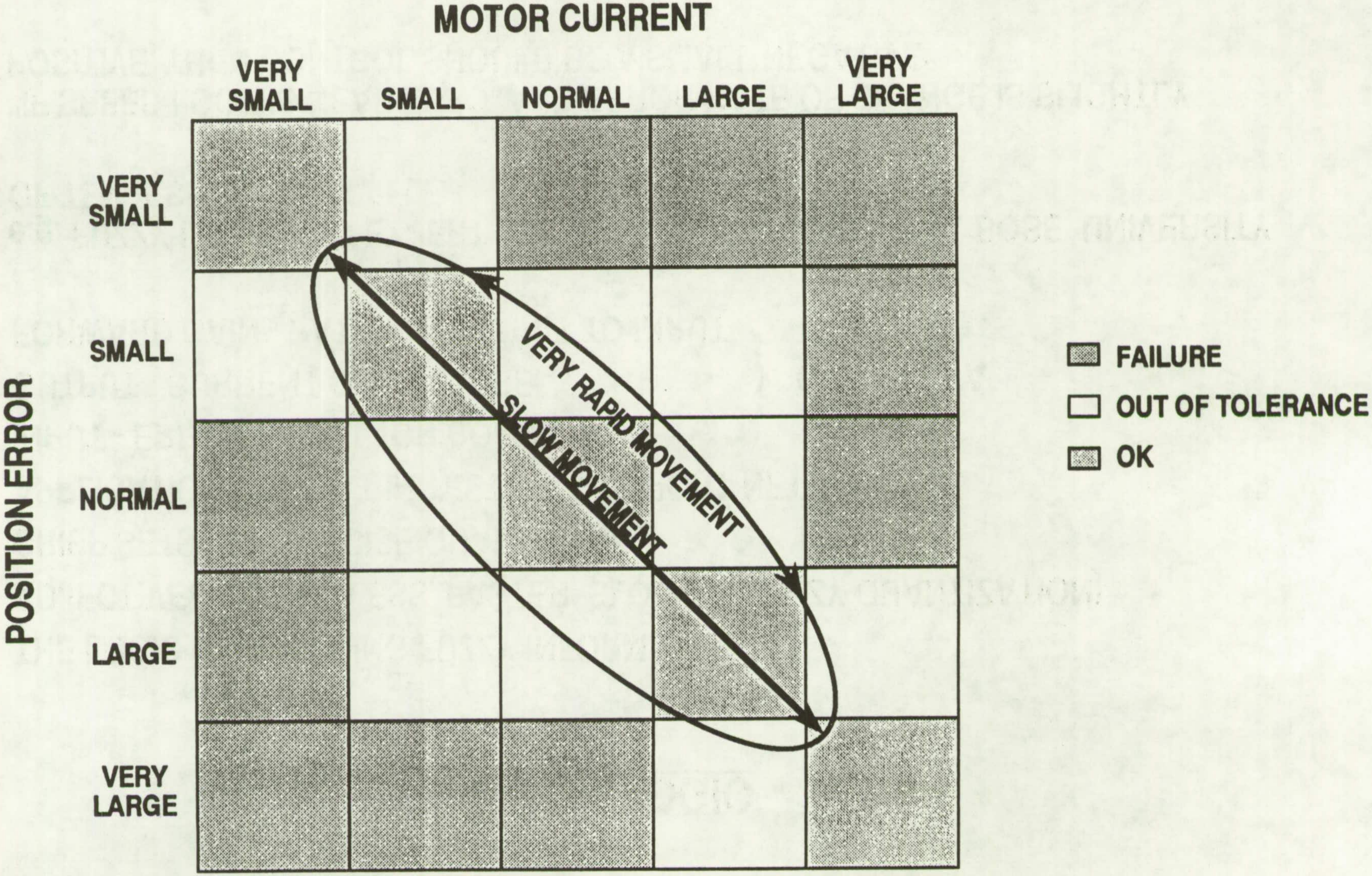
e.g. FUZZY LOGIC AND EXPERT SYSTEM APPLICATIONS - B. K. BOSE, UNIVERSITY OF TENNESSEE, KNOXVILLE

"IF SPEED LOOP IS NEAR ZERO, AND ERROR RATE OF CHANGE IS SLIGHTLY POSITIVE, THEN CONTROL SHOULD BE A SMALL NEGATIVE"

RESULT - CONTINUOUS NON INTRUSIVE MONITOR OF SERVO GAIN

H-91.01-9 pm

FUZZY LOGIC RULE TABLE



EMA SPECIFIC REQUIREMENTS

(BOTTOM UP) - DESIGN ARCHITECTURE FOR:

COMPONENT LEVEL - DIAGNOSTICS (NEURAL NETWORK, NOT IN REAL TIME) (EVENTUAL INCIPIENT FAILURE DETECTION)

SUBSYSTEM LEVEL - RAPID DETECTION (NOT INTRUSIVE MEASUREMENT, WIDE DYNAMIC RANGE, FOUR QUADRANT OPERATION)

APPROACH TAKEN - FUZZY LOGIC OBSERVED (CONTINUOUS MONITOR OF INPUT (COMMAND) AND OUTPUT (CURRENTS & POSITION)

EVALUATION & CALIBRATION - HYBRID ANALOG COMPUTER AT PURDUE UNIVERSITY (ALLOWS MAJOR FAULTS TO BE INTRODUCED WITHOUT ENDANGERING PERSONNEL OR EQUIPMENT)

IGH92-004.3

Rapid, VHM System For Electrical Actuation/Power/Avionics

Task Objectives/Benefits

Objective(s):

Develop and demonstrate automated, rapid self-check systems for advanced electrical actuators and effectors, power and avionic systems including more-electric ground support equipment (GSE)

Applicable Vehicles:

ELV, NLS, Upper Stages, STS Upgrades, AMLS, ACRV

Benefits:

- Transfer rapid prototyping steps to improve vehicle assembly, ground operations and launch sequencing
- Demonstrate "bottoms-up" HW/SW platform for interface to total IHM system
- Reduce launch system costs
- Improve launch system operability, reliability and safety

Demonstration/Bridging Approach

Task(s):

1. Develop specific elements to existing (SBIR II) detailed models/simulations of vehicle and GSE systems under normal and fault conditions
   a. Insert fault, document parameter variations
   b. Validate model predictions, characteristics on subsystem hardware
2. Integrate HW/SW for rapid BIT on existing DSPs to demonstrate health indicators on selected electrical equipment (EMAs and power system)
3. Test/demonstrate BIT under fault conditions and selected fault modes to validate technology/models
4. Develop interfaces to top level IHM system and automate responses to detected fault modes
5. Validation assessment of technology

Available Facilities:

LeRC Technology Demonstration Facility, Autonomous Power System, EMA Laboratory, and University of Purdue Hybrid Computer Facility

Technology Description

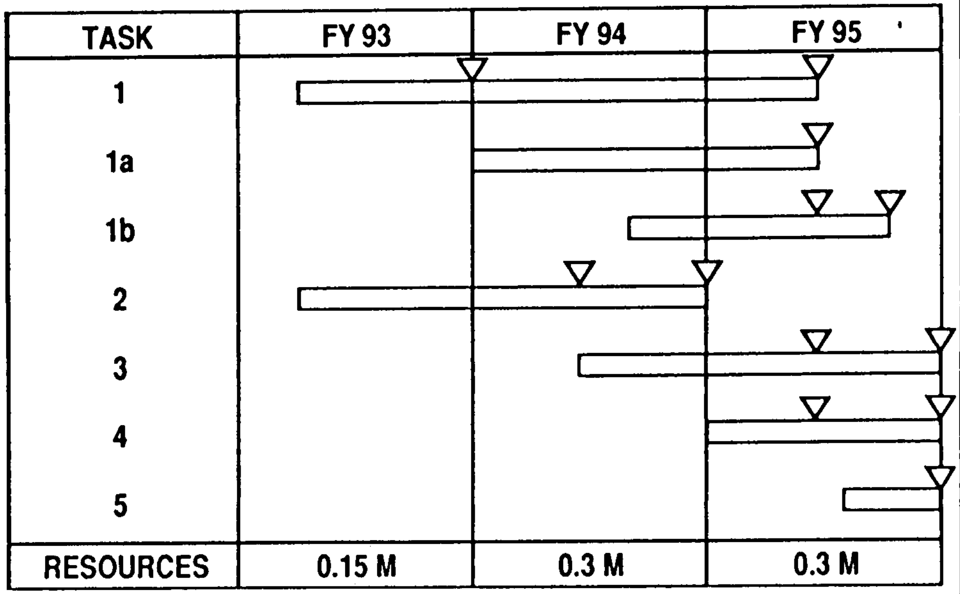
NASA Technology Readiness Level: 5

Specifications:

- Distributed intelligence/controls/monitoring in electrical equipment both on vehicle and in GSE
- Rapid, smart Built-in-Test (BIT) using embedded microprocessors (DSP) with fuzzy logic for self-check and correction
- Minimize requirements for sensors, data transfer/storage and centralized computing
- Real-time pre-, post-, and in-flight health assessment and analysis
- Accurate and reduced-order models/simulations for rapid prototyping, testing and fault studies
- Use LeRC developed Framemaker for graphic visualization

LeRC Contact: Gale R. Sundberg, (216) 433-6152

Schedule/Cost



GRS92-011.1

FAULT TOLERANT SYSTEM TESTING

Norm Osborne
and
Dave Wilks

Fault-Tolerant System Test Bed

- Objective of Test Bed
  - Fault Detection Functional Tests
  - Health Monitoring Function Tests
  - System Performance Testing
  - System Optimation Demonstration
  - System Development
  - Subsystem Development

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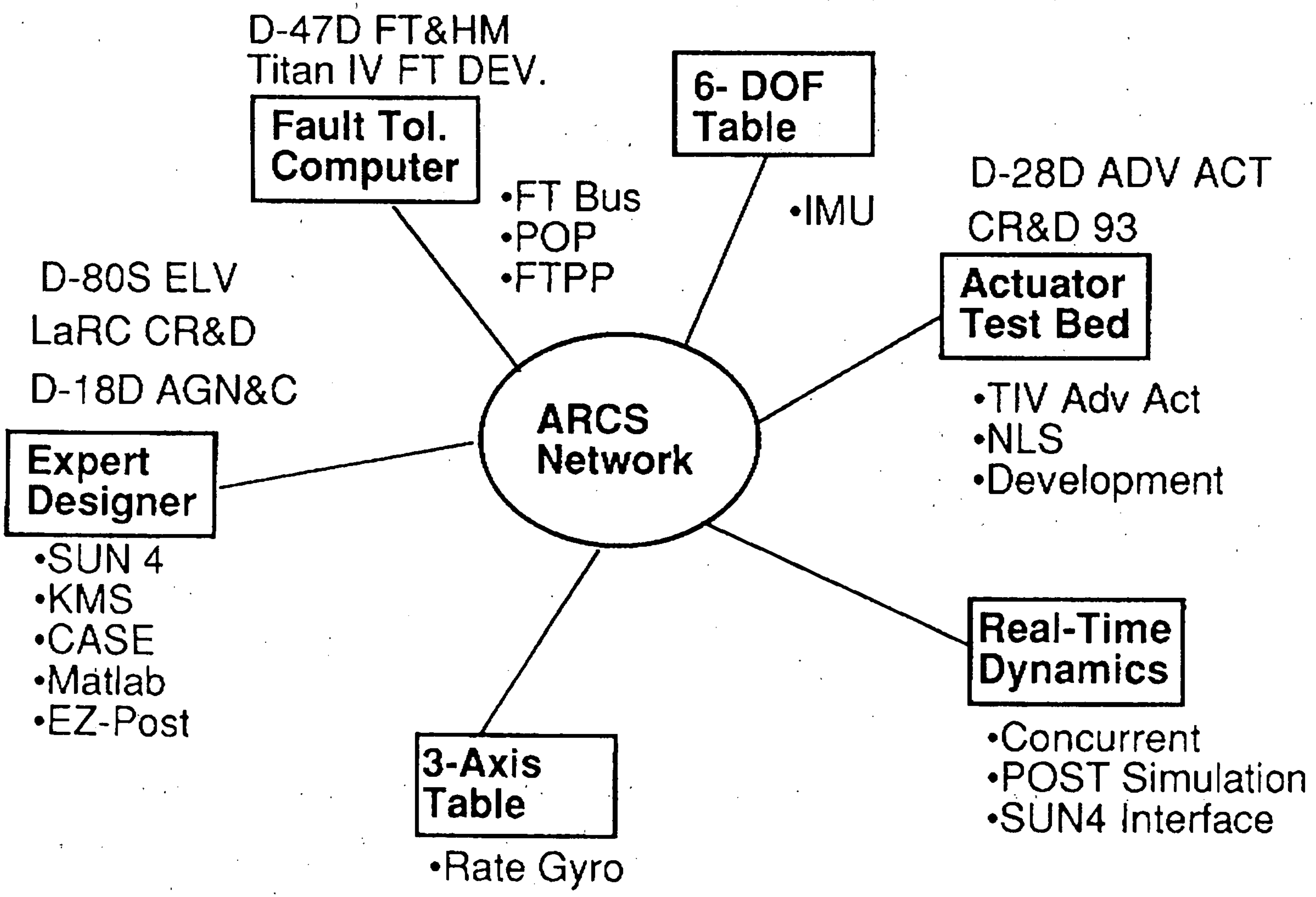
Fault-Tolerant System Test Bed
Relationship with IR&D/ CR&D--Real-Time Lab



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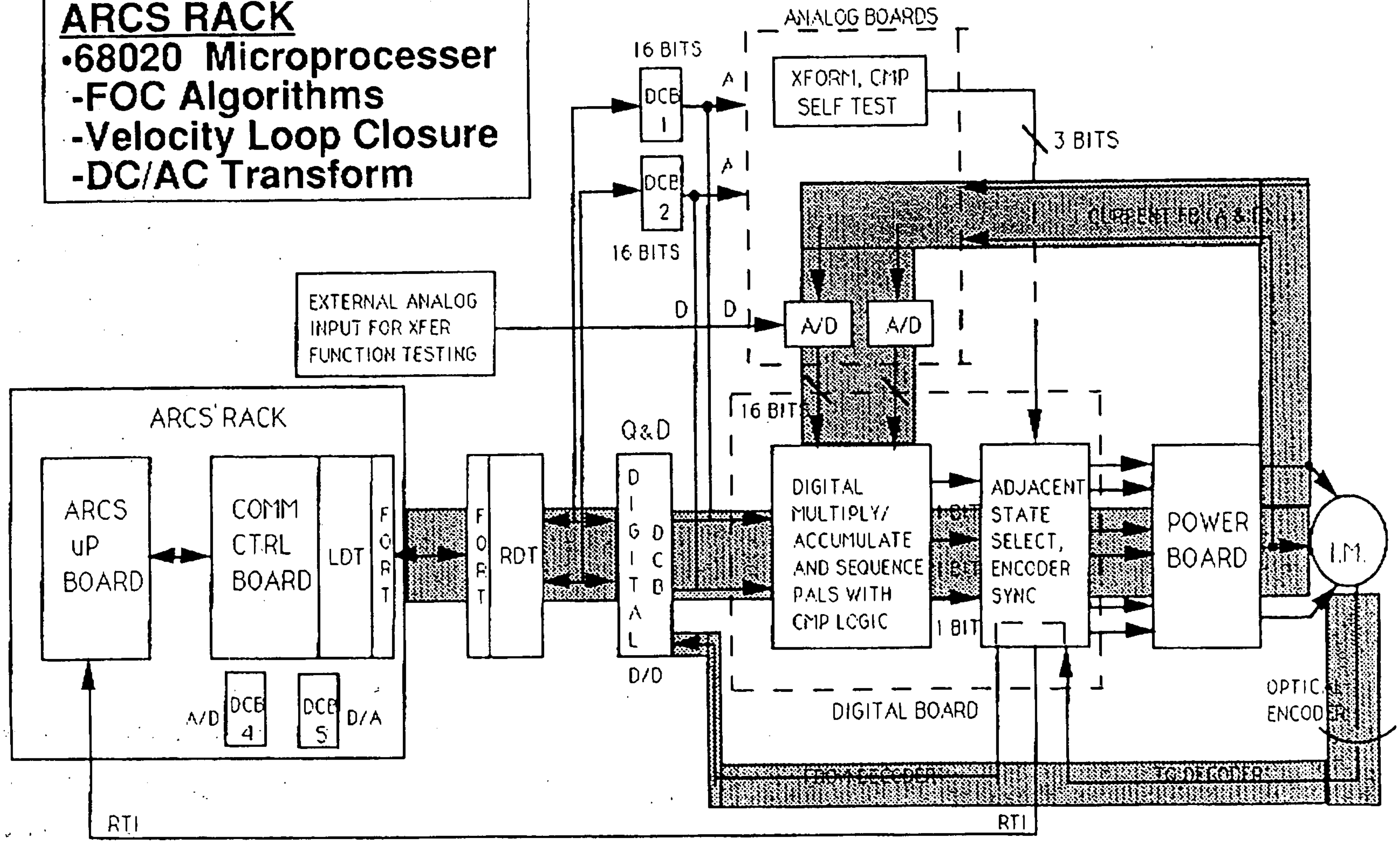
Fault-Tolerant System Test Bed
EMA/ARCS TOPOLOGY

ARCS RACK
- 68020 Microprocesser
  - FOC Algorithms
  - Velocity Loop Closure
  - DC/AC Transform



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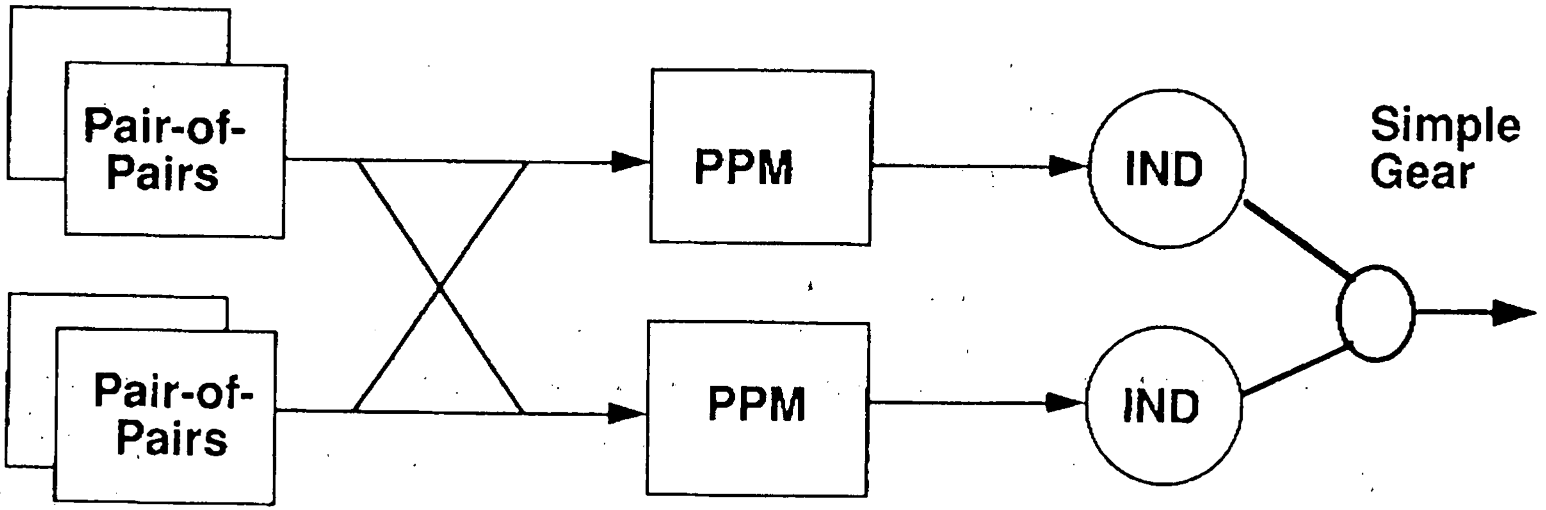
Fault-Tolerant System Test Bed

Redundancy with Induction Motors

- All Software Approach Allows Fault Tolerant Embeded Computer Applications--such as Pair-of-Pairs or FTPP
- Motor Drive Can Be EitherPulse Placement or Pulse Width Modulation
- INDUCTION Motor Output Drives a Simple Gear Train



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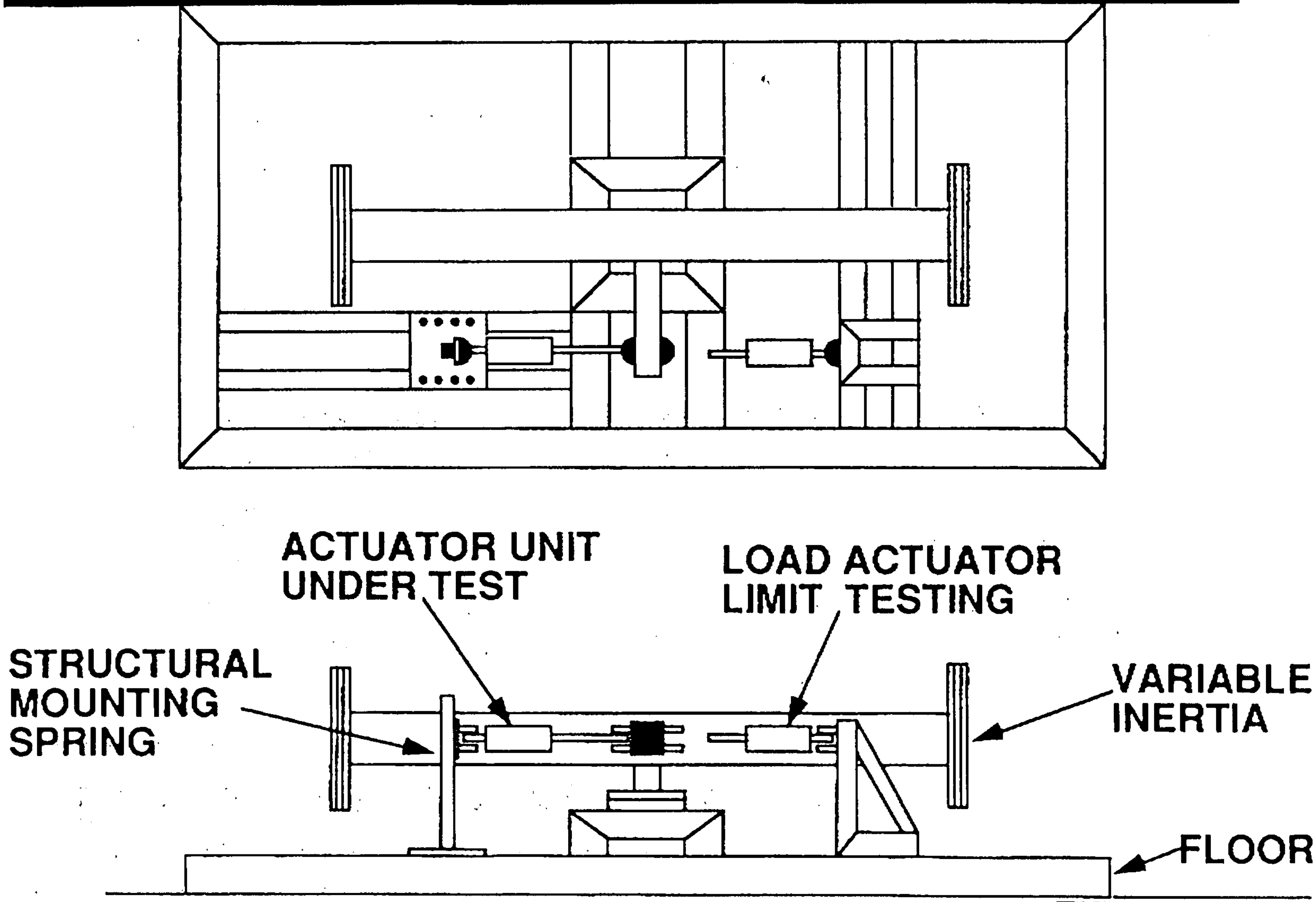
Fault-Tolerant System Test Bed
Horizontal Pivot Pendulum Test Stand



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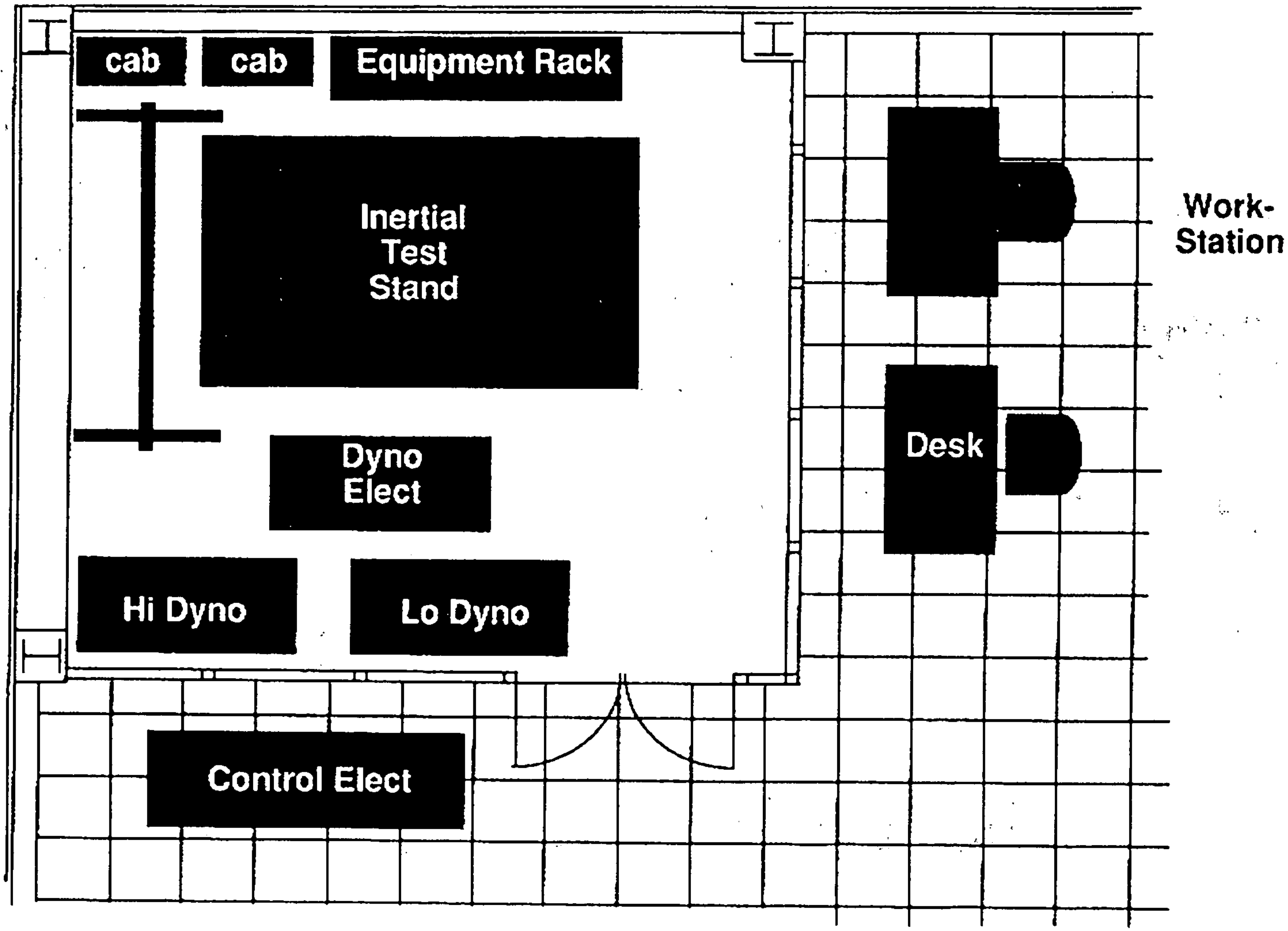
Fault-Tolerant System Test Bed

Actuator Test Bed Layout



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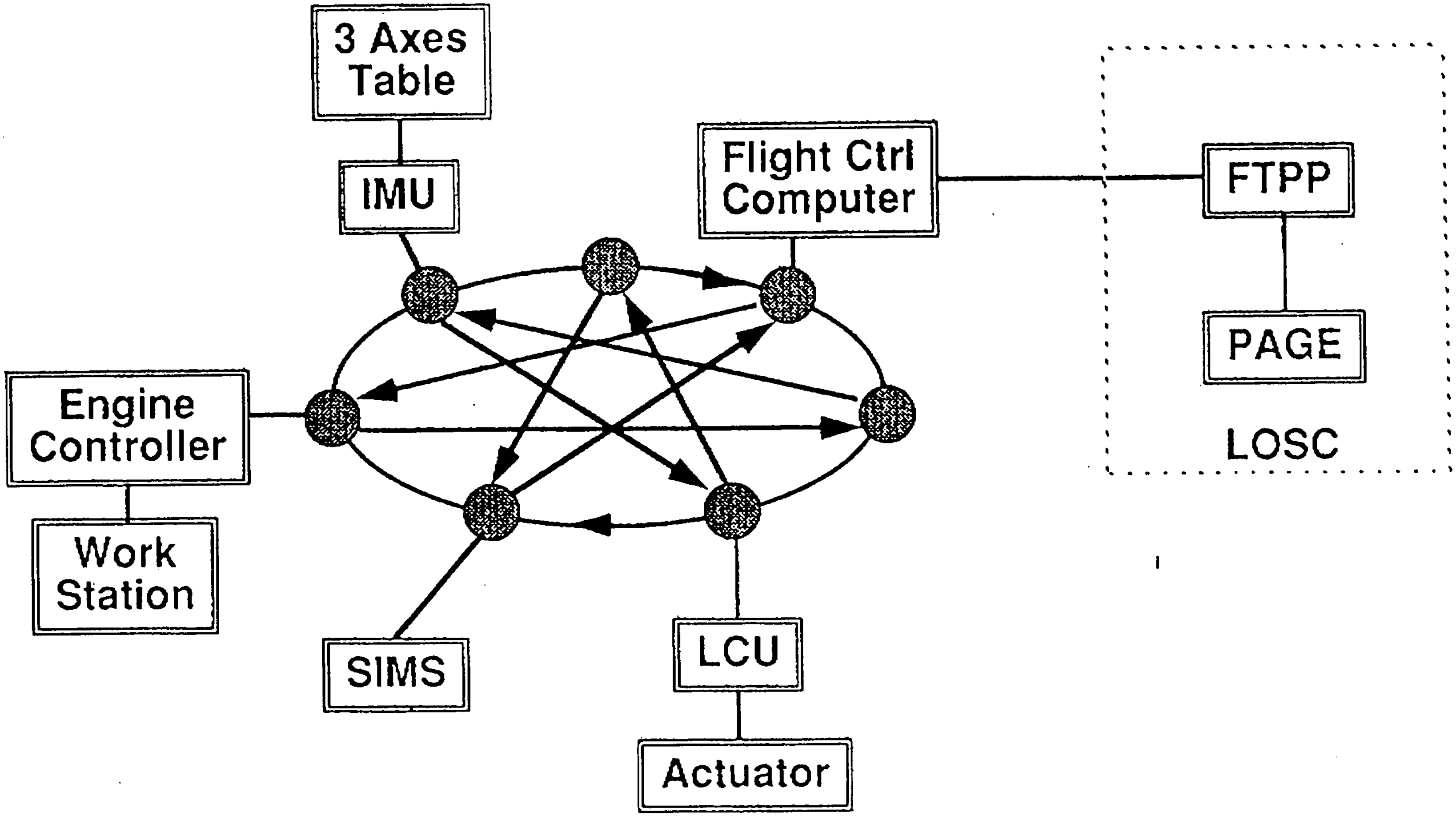
1993 FTA/HM Lab Demonstration Overview



Fault-Tolerant System Test Bed
Summary

- **Flexible Test Bed**
  - Systems
  - Component
  - Functional
  - Performance
- **Multiple User**
  - Internal Research and Development
  - Airforce
  - NASA (multiple center)

MARTIN MARIETTA

FMEA'S AND FAILURES IN TEST

Rae Ann Weir / MSFC EP64
205-544-7146

During the time frame from November 1991 to the time of this workshop, 20 failures were recorded during testing of EMA's. Failures documented include those during the development and test of Marshall's in-house actuator and hardware brought in for test and demo. Failures were divided into two categories. The first category includes problems identified as areas which still require investigation. These are listed under Credible Failures/Problems. Problems associated with EMI and grounding were seen with each piece of hardware brought into the lab. High power electronic problems accounted for the largest number of failures. This may be due to the fact that some development failures were documented for this presentation. It was soon discovered in the lab, with the rotational forces associated with these actuators, that more attention must be paid to the structural interfacing, at least for test purposes. The other category contains failures which include problems considered not to be applicable to a flight type actuator. These are the Noncredible Failures. For example, the motor failures which were documented occurred due to using off-the-shelf and not necessarily optimized hardware. This is not to say that a shorted motor would not be a credible failure, but failures of that nature have not been seen in test.

FAILURES IN TEST

20 Failures were recorded at Marshall during EMA testing activities. These include failures during development and test of Marshall's actuator and failures in hardware brought in for test and demo.

Credible Failures/Problems	NON CREDIBLE FAILURES
EMI/Grounding	Motor
High Power Electronics	Low power circuitry
Testing/Vehicle Structural Interfacing	Power

An attempt was made to determine a plausible fault tree for the EMA. Due to the different design philosophies, including EHA's, a single fault tree would probably exclude some of the failure modes of those designs I am less familiar with. What has been prepared are two levels of a fault tree with the first level being generic to all designs. Each actuation system may be broken down into sub-components: a power source, the control electronics, motor, actuation mechanism, sensors, and interfaces. While each actuator may have a different design philosophy, each utilizes some from of each of the sub-components listed. The next level is more particular to the design philosophy. This level includes a breakdown of each actuation sub-component into the elements which could cause a failure. The next step would be to identify each fault particular to an element. With each fault, a signature of the failure and a means of detecting it is important.

ELECTRICAL ACTUATION SYSTEM
FAULT TREE

POWER	• High Power Short Open Explosion • Avionics Power
CONTROL ELECTRONICS	• Low Power • Sensors • High Power PWM Current Bridge Regeneration Supporting Electronics
MOTOR	• Windings • Drive Shaft • Commutation Sensors • Magnets
ACTUATOR	• Gear Train • Roller/Ball Screw
INTERFACES	• Cabling • Connectors • Structural Attach Points
SENSORS	• Current • Rate • Position • Force

EP64

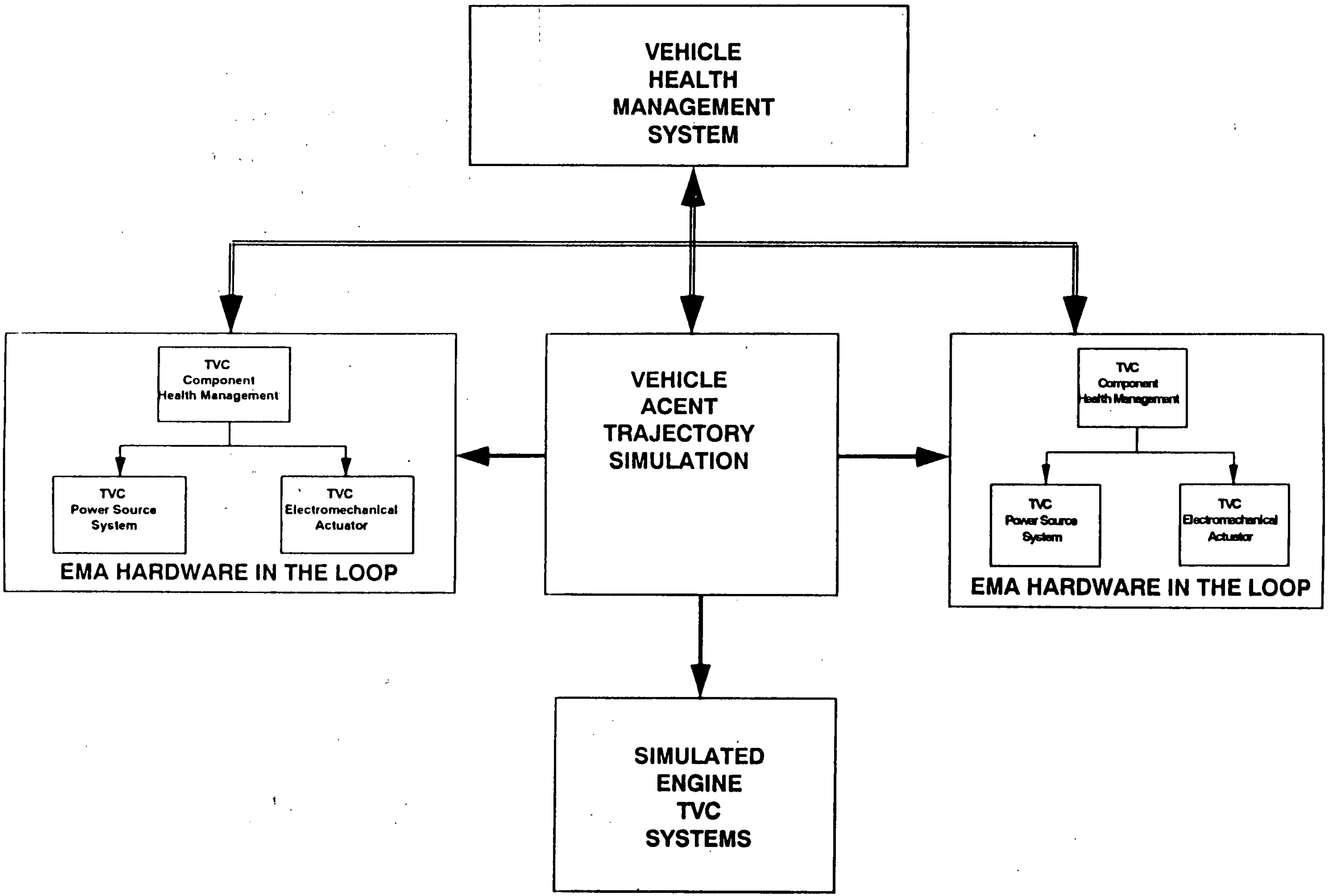
Task : Develop and implement a Vehicle Health Management (VHM) platform for Electromechanical TVC actuation systems using actual hardware and vehicle simulations in the loop.

MSFC is proposing to upgrade existing facilities in order to implement a platform for the testing and development of Vehicle Health Management (VHM) for electromechanical actuators. The proposed platform will incorporate hardware, including power sources and vehicle as well as hardware simulation. The first step will be to determine the requirements and tools to implement a VHM hiearchy, working with a bottoms up philosophy. From there, each level of technology will be demonstrated until a full actuation system VHM level is attained. This platform will be used by MSFC to investigate VHM algorithms, redundancy, etc. It is our hope that NASA and Industry will take advantage of these facilities for further development of EMA's.

HARDWARE DEMONSTRATION OF VHM SYSTEM

- Establish Requirements, Sensor Suites, and Algorithms for VHM hierarchy
  - BIT
  - Component Level
  - System Level
- Implement VHM Platform with hardware in the loop
  - Component Level Health Management
  - Vehicle Simulation
  - System Level VHM
- Demonstrations
  - TVC EMA System
    (MSFC, Moog, Honeywell, Allied Signal, Boeing, GD)
  - Apply similar techniques to EMA Valve Actuation System

MSFC EMA\TVC PLATFORM FOR VEHICLE HEALTH MANAGEMENT DEMONSTRATIONS



FACILITIES, HARDWARE AND SUPPORT

- Component Development Laboratory (Bldg. 4656)
  Two inertia load simulators, soon to be equipped with programmable force generators.
- Prototype EMA hardware
- In-house support may be obtained from EB and ED laboratories
- Contractor support will be required for software development.
- Contractors will be invited to use test platform.

GenCorp
Aerojet

Propulsion Division

Summary/Status

- Detailed Design Of The EMA Assembly Complete
- Digital Closed Loop Control Approach Demonstated
- Performance Characteristics For Major Components Demonstrated
- Fabrication Of Electronics In Progress
- Fabrication/Assembly Of EMA Scheduled For Completion In FY 1993

Tests Confirmed Operating Characteristics Of The EMA Components

Motor Driver Circuit Board

- Test Of Basic Drive Circuit Functionality
  - Output Commutation
  - PWM Frequency Characterization
  - Speed vs. Input Voltage Linearity
  - Forward /Reverse Operation

- Test Of Health Monitoring Circuitry
  - Drive Current Sensing
  - Board Temperature Sensing/Conditioning
  - Motor Temperature Sensing/Conditioning

Microcontroller Circuit Board

- Evaluation Of 87C196KC As The Controller For EMA System
  - Closed Loop Control
  - Sensor Interfacing

- Test Of RTD Converter Circuit With 87C196KC Microcontroller

Tests Confirmed Operating Characteristics Of The EMA Components

Gear Reducer

- Acceptance Tests For Efficiency, Backlash, Torque, Torsional Stiffness, And Input Speed
- Cryogenic Tests Of The Gear Reducer To Verify Thermal Resistance
- Efficiency Tests At Low Temperature

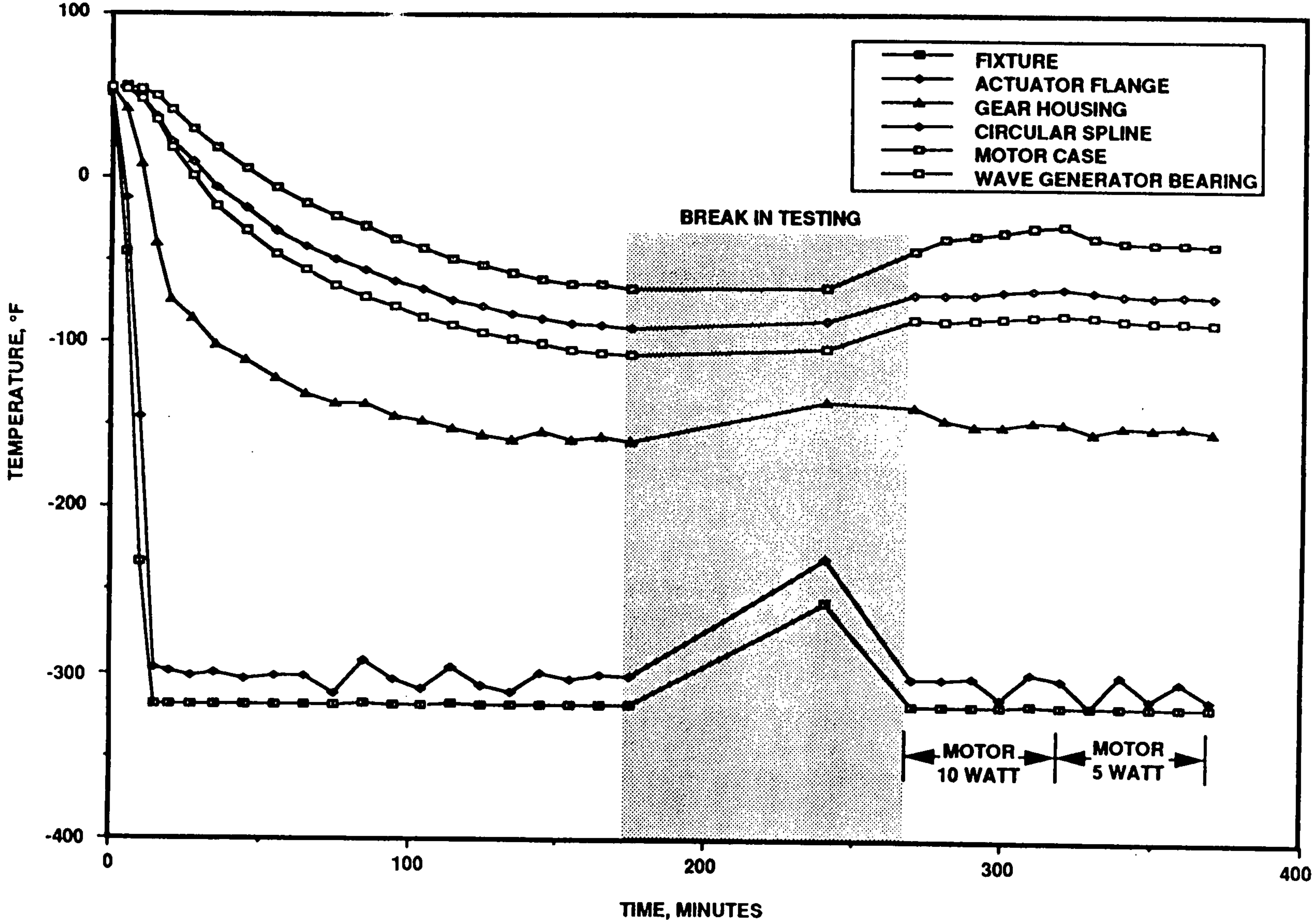
Motor Assembly

- Speed-Torque Characterization Tests
- Test Of Drag Torque Resulting From Failed Motor

GenCorp Aerojet

Propulsion Division

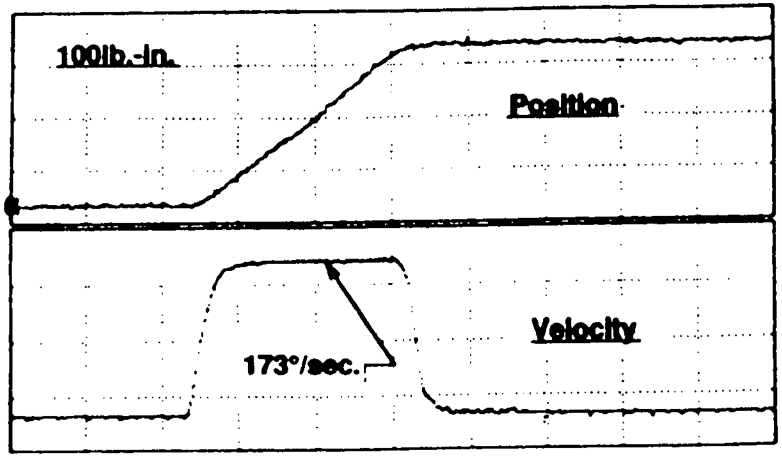
EMA Temperature Profile Has Been Characterized By Test

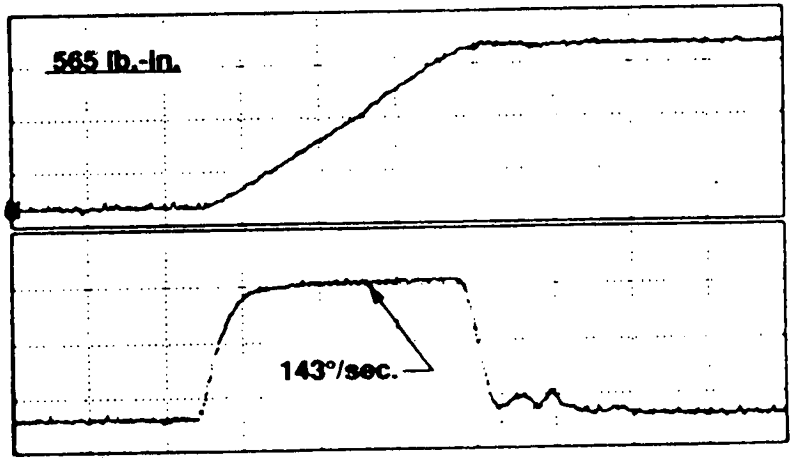


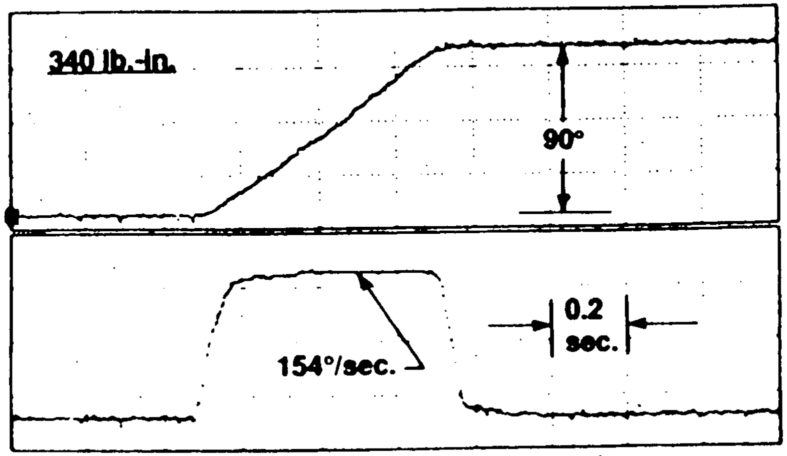
GENCORP AEROJET

Propulsion Division

Performance Tests Demonstrated Stable Operation Over Load Range



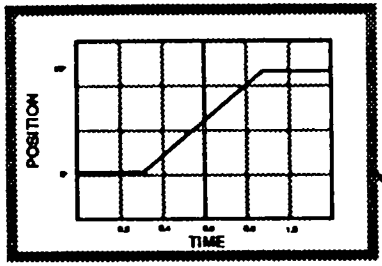




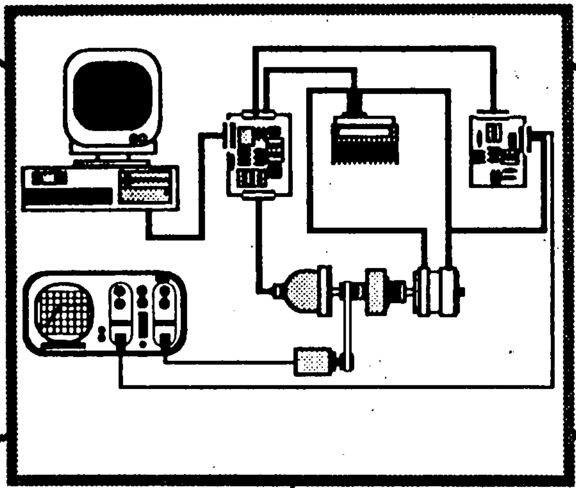
GENCORP
AEROJET

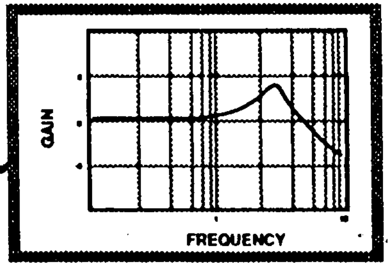
Propulsion Division

EMA System Was Tested To Verify Proof Of Concept

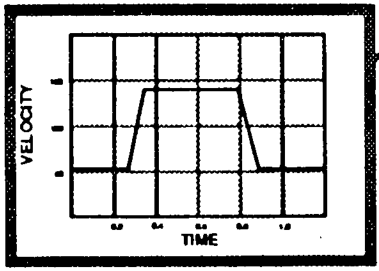


- Step Response
- Position Accuracy

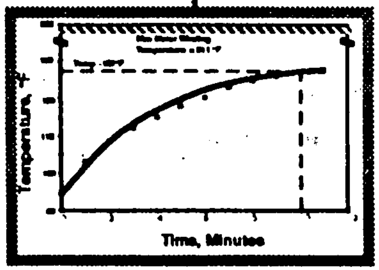




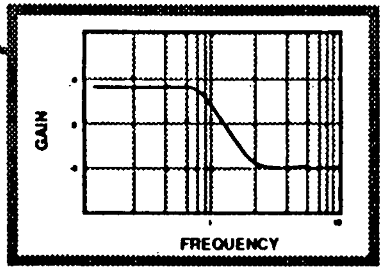
- Frequency Response (Gain)



- Slew Rate



- Holding Torque
- Duty Cycle



- Frequency Response (Phase)

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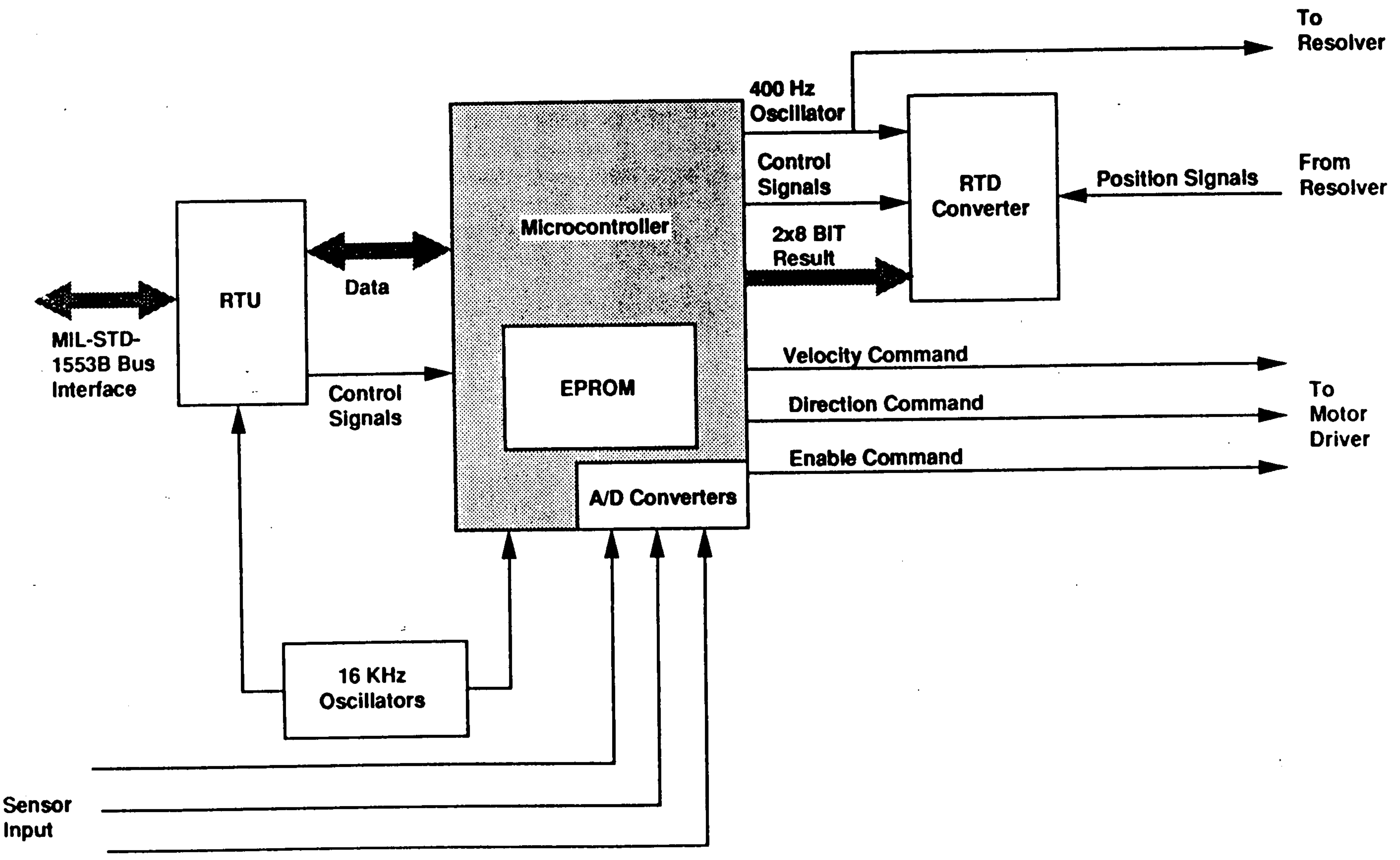
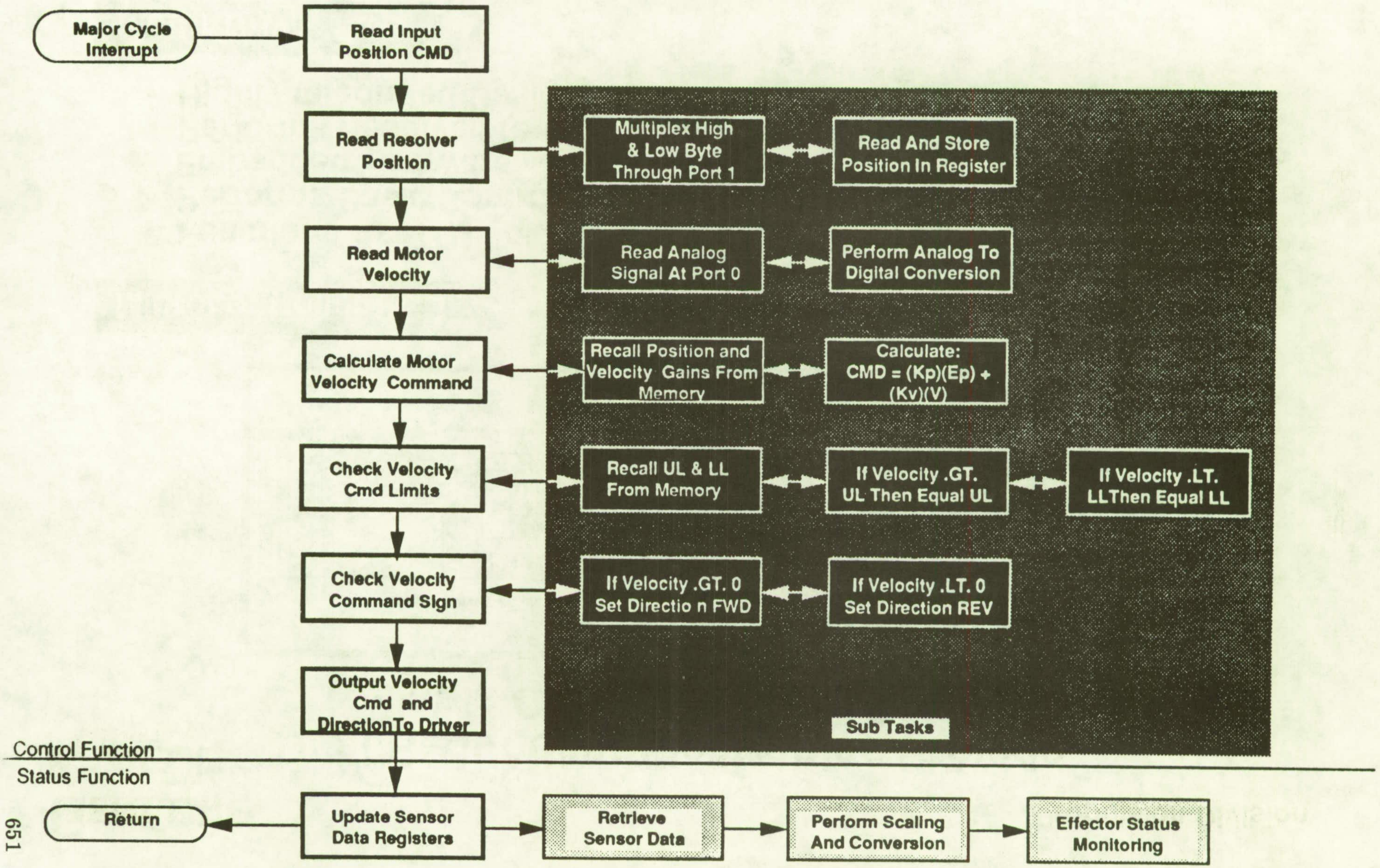
Microcontroller PCB Design Is Based Upon The 87C196KC Microcontroller



Embedded Software Performs EMA Control Functions



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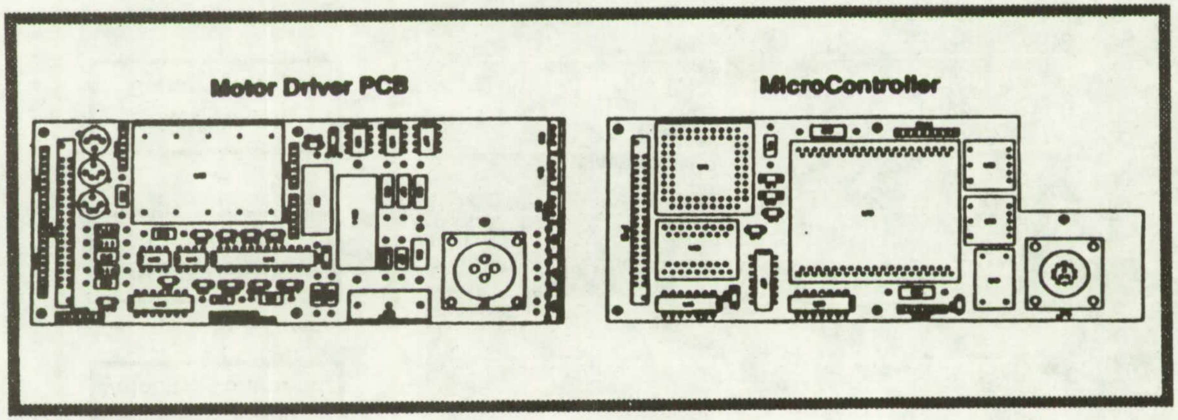
Dual Redundant Electronics Provide Reliable Control System Design



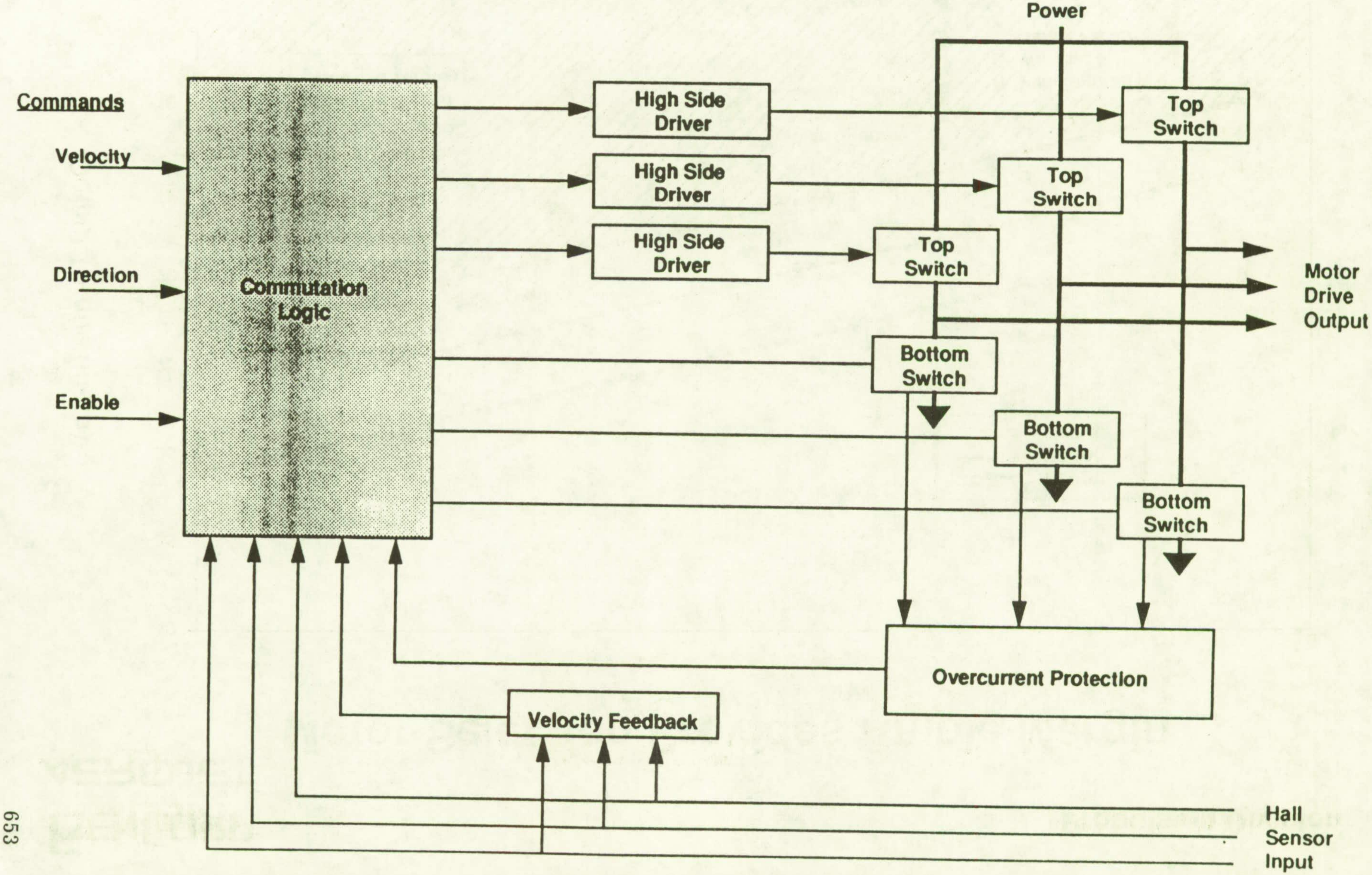
Microcontroller PCB

- Functions As RTU For MIL-STD-1553B Serial Data Link
- Performs Basic Control And Health Monitoring Functions Using Embedded Firmware
- Performs Resolver To Digital Conversion For Position Feedback
- Highly Integrated Design

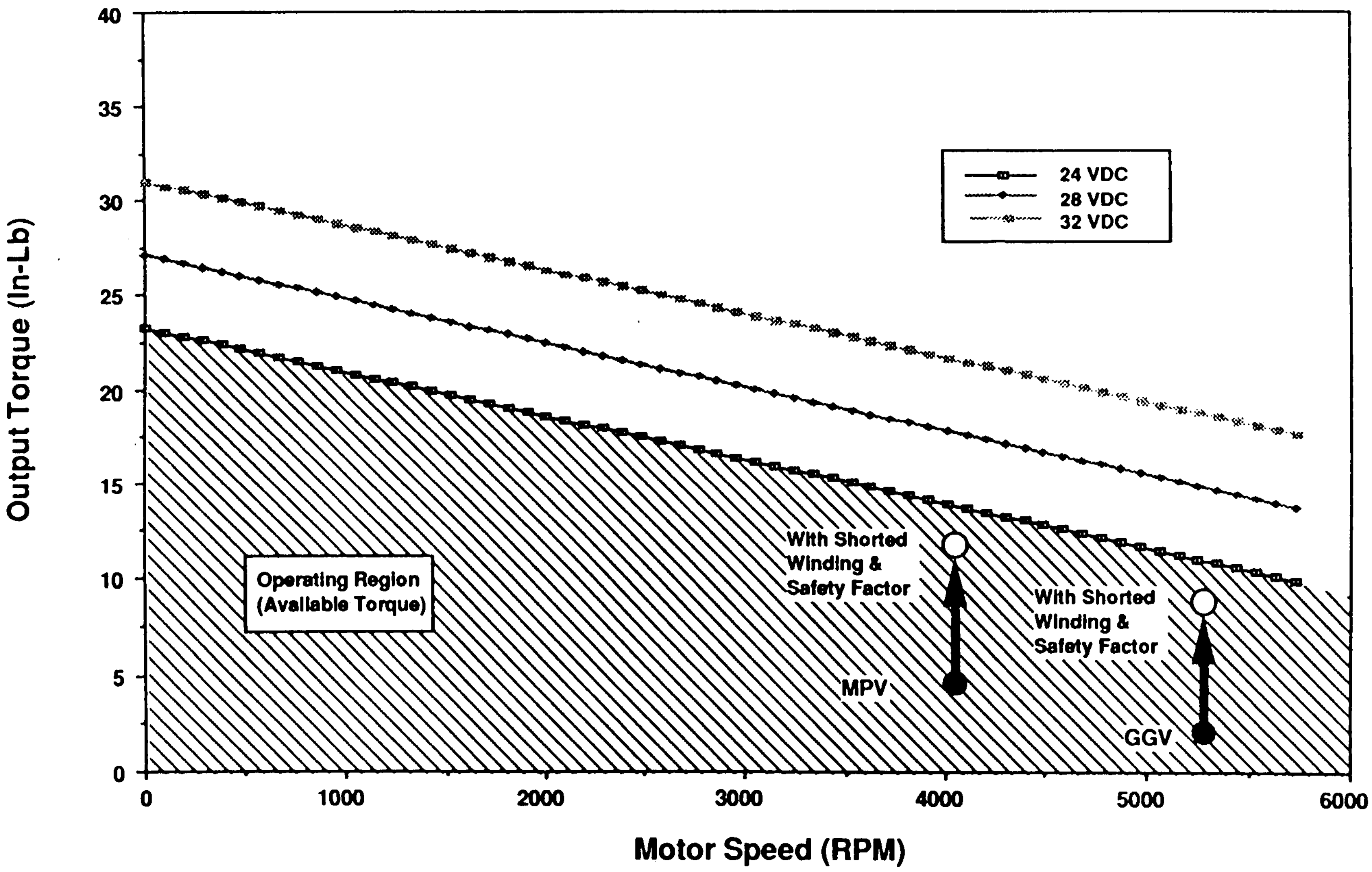
Motor Driver PCB

- Performs Motor Commutation And Power Switching
- Serves As Power Source (DC-DC Conversion, Filtering And Distribution) For On-Board Components
- Provides Signal Conditioning For Sensor Signals

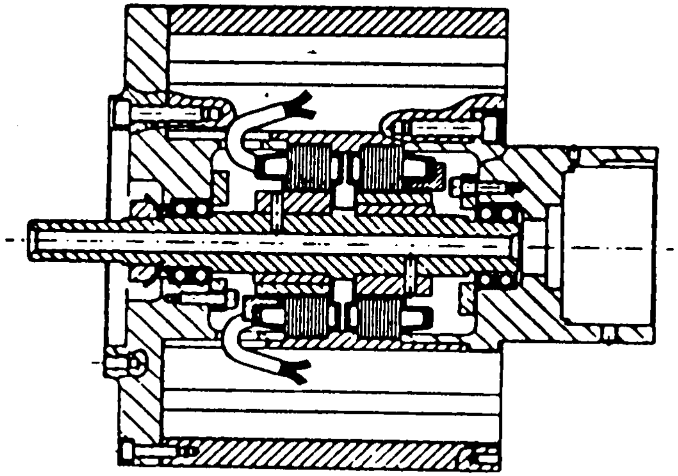
Basic Commutation Function Is Performed By Motor Controller IC



Motor Selection Provides Ample Margin



Motor Assembly Design Focuses On Reliability



FEATURES

- Redundant High Torque Brushless DC Motors
- Common Motor Drive Shaft (Eliminates Clutch Mechanisms)
- Duplex Bearings For High Vibration Environment
- Mounting Cavities For Integral Dual Channel Electronics

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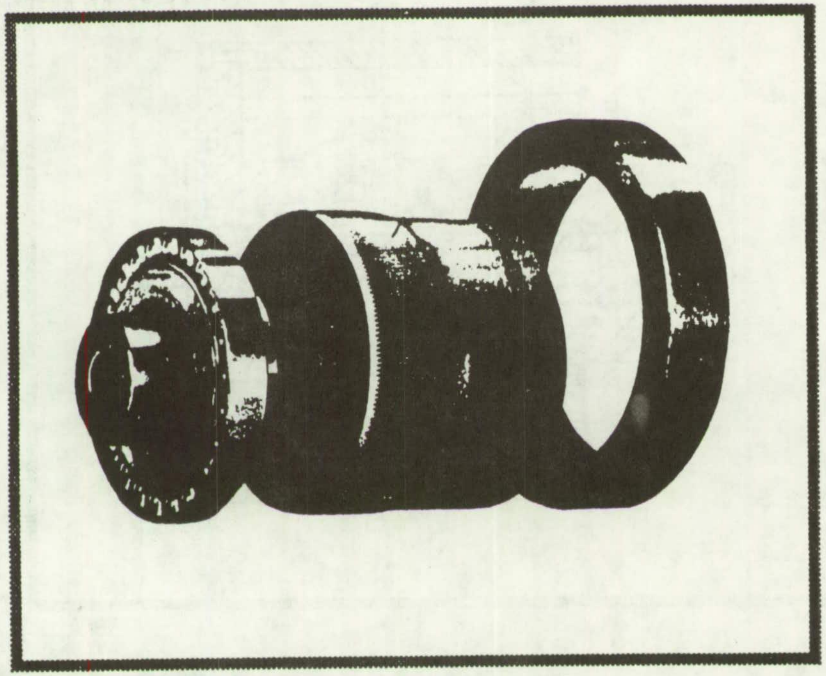
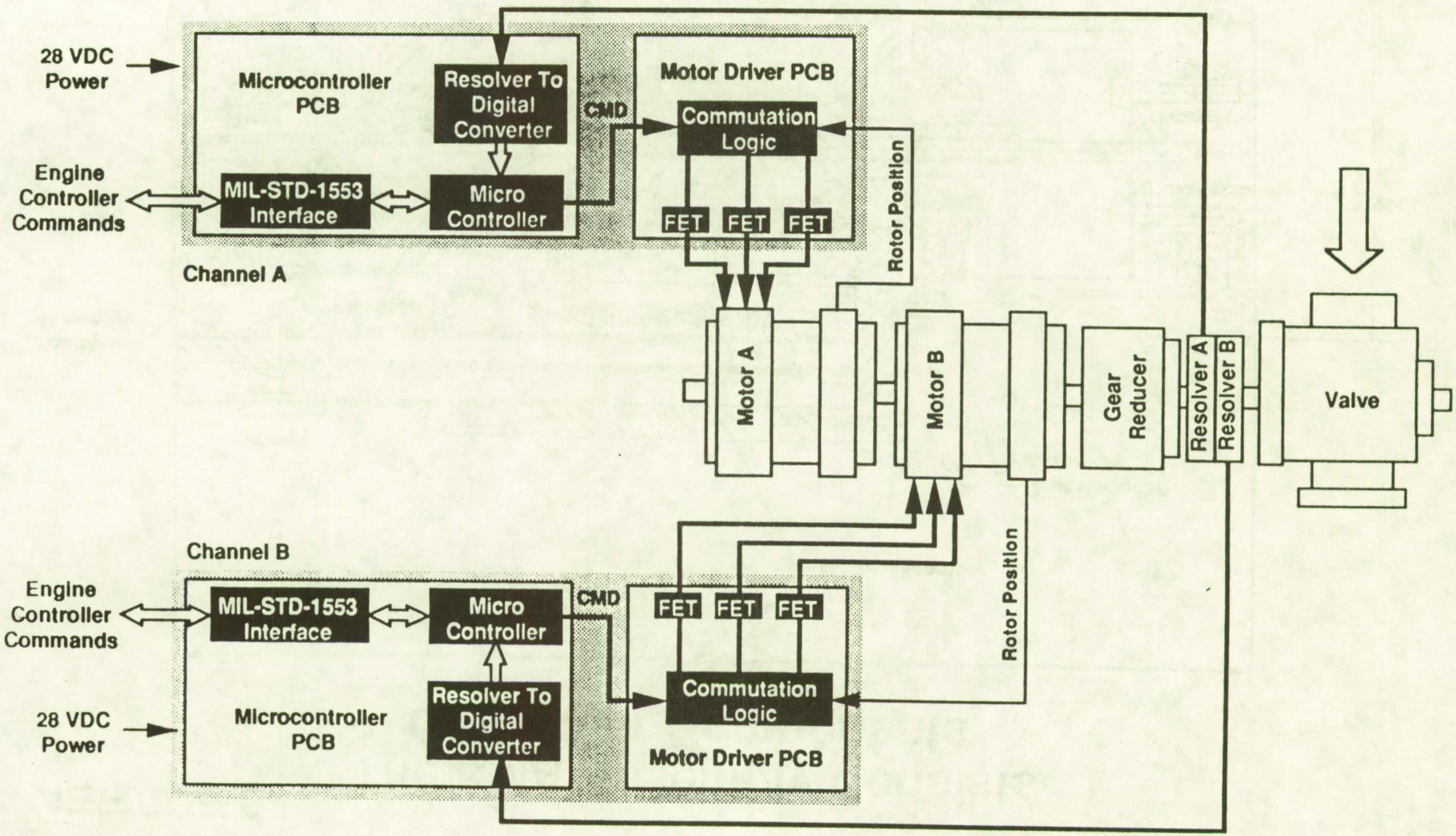
Gear Reduction Is Accomplished Using Harmonic Drive Design



FEATURES

- Single Stage Reduction
- High Torque Capacity
- High Torsional Stiffness
- Zero Backlash
- Compact Design

EMA Provides Redundant Closed Loop Digital Control



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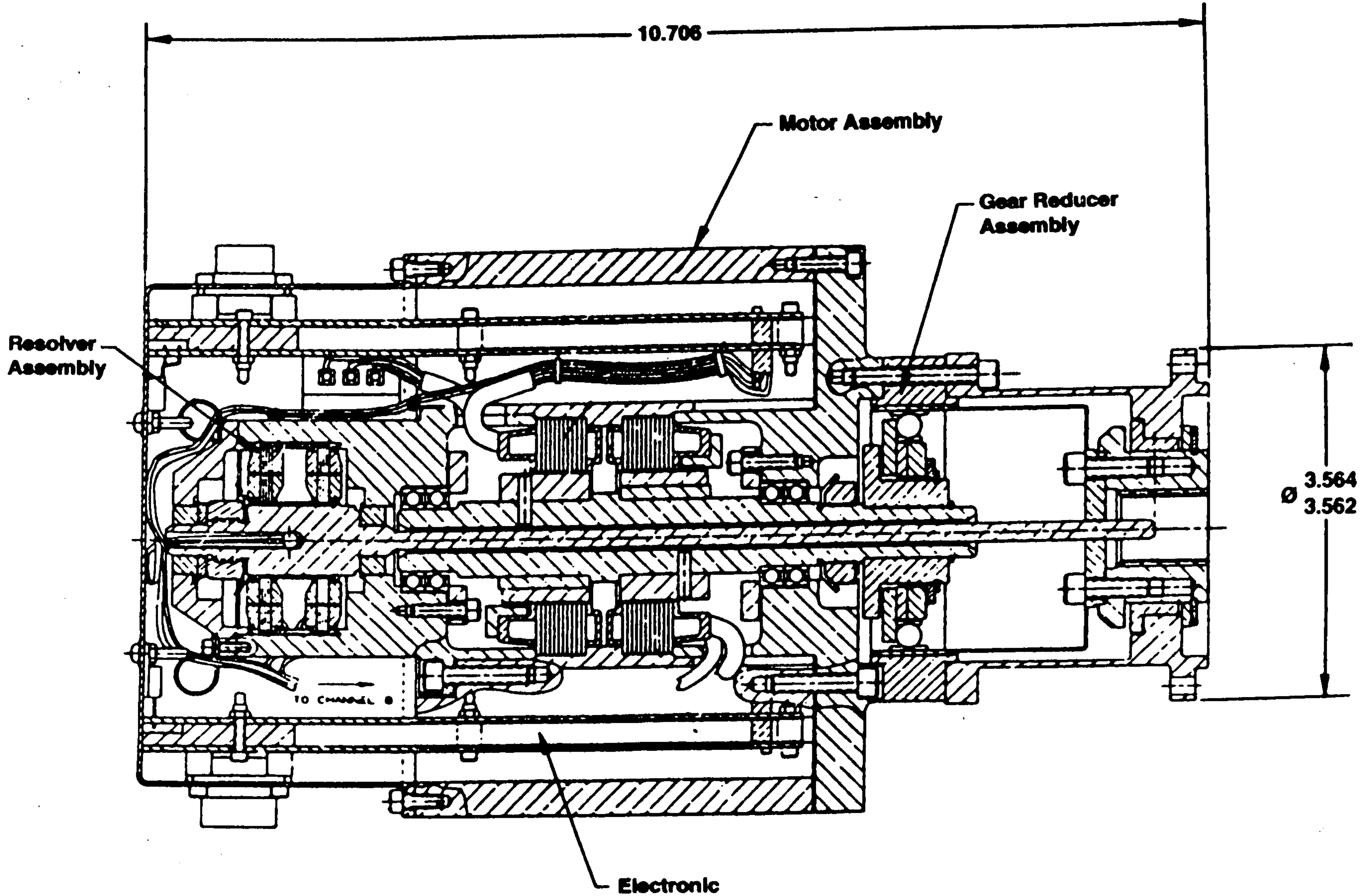
The EMA Assembly Consists Of 4 Major Components



Combined EMA Features Provide A Unique Technology

Technology Modular, Self Contained Actuator

- Electromechanical Design Eliminates Problems Associated With Hydraulics And Pneumatics
- Complete Electrical/ Electromechanical Redundancy For Increased Reliability
- Integrated Electronic/ Mechanical Package Which Can Be Mounted Directly To Cryogenic Valves
- Application Of Digital Technology For Local Closed Loop Control, Communication And Health Monitoring

Replaces

- Hydraulic And Pneumatic Actuator Technology

Application

- Modular Design And Simplified Interface Allows Adaptation To Any On/Off Or Modulating Valve Application

Objective

- Demonstrate A Reliable, Low Cost Propellant Effector System Using An Electromechanical Actuator

Approach

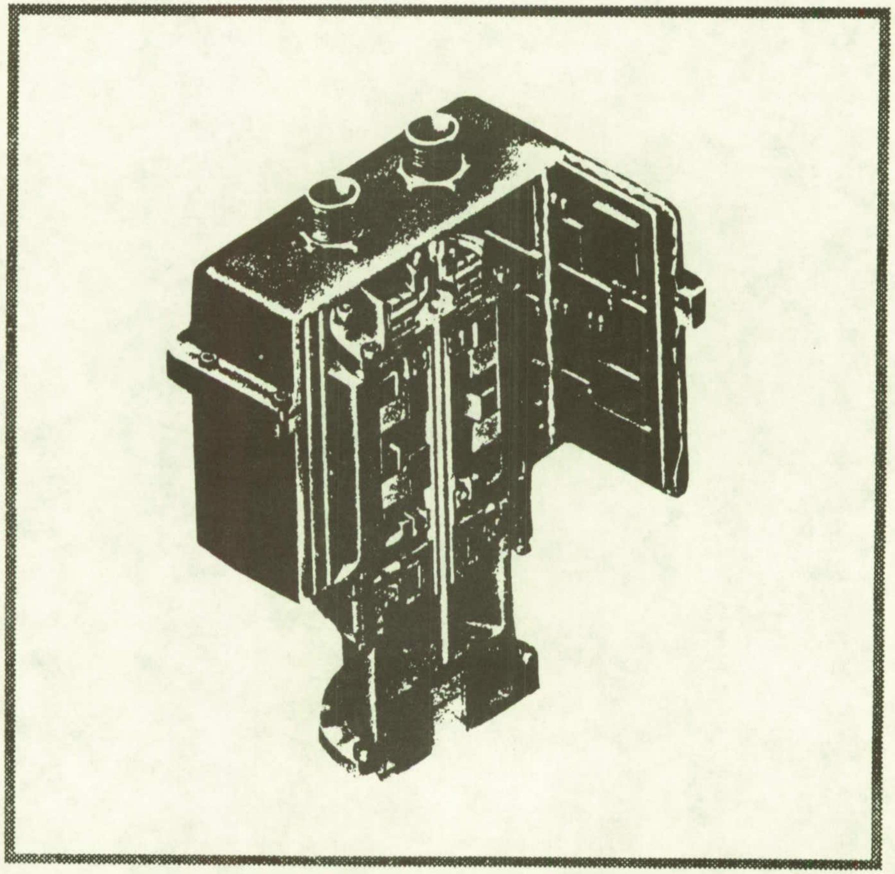
- Phase I - Preliminary Design
  - Requirements Definition
  - Preliminary Design of Valve And EMA
  - Testing Of Low Cost Technologies
  - Trade Studies

- Phase II - Detailed Design
  - Detailed Design Of EMA
  - Detailed Analyses; Reliability, Thermal, Structural, Vibration
  - Dynamic Model EMA
  - Fabricate Three Full Size EMA Assemblies
  - Test Valves At MSFC

Propulsion Division

Space Transportation Main Engine Electromechanical Actuator Design

29 September 1992



SESSION XI

SPLINTER SESSIONS

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SESSION I: ELA SYSTEMS

1. Assess ELA technology readiness as demonstrated by the performance capabilities of the Workshop prototype hardware. Has feasibility been definitively established?

2. Identify Critical Path elements on completing ELA Technology Bridging development by FY-95, considering:
   - ELA systems demonstrations (actuator/controller/power source)
   - SSME Technology Test Bed (TTB) hot fire demonstration
   - a mechanism for NASA & Industry to down-select candidate ELA systems for TTB

3. Discuss the utility of a NASA ELA System Design Handbook as an output from ELA Technology Bridging.

4. Outline an ELA advocacy strategy for transformation of ELA-TB development into flight systems for:
   - early HLLV by FY-96, including industry supported cost/schedule/procurement plans.
   - SRM/ASRM retro-fits
   - Centaur retro-fit

5. Assess the vitality of Industry supported ELA prototype developments; will NASA support be necessary ?

6. Assess the pros & cons of ELA technology fly-offs under ELA-TB, including
   - EMA vs EHA
   - ELA and PSS systems compatibility
   - Roller vs Ball screw transmissions

7. Recommend the format for the next ELA TIM/Workshop/Conference: WHAT, WHEN & WHERE.

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SESSION I. ELA SYSTEMS

October 1, 1992

Question 1. Yes, ELA has demonstrated technology readiness and has established feasibility. **Note**: The whole group agreed with this.

Question 2. The critical element of the ELA Bridging program is the hot fire test. This is not the only thing but it is essential if we are to sell this technology to a program manager.

Question 4. NASA has to focus in on a target and provide system requirements. This is a must for evaluating various system fairly.

Question 5. Industry can not continue to support this kind of effort very long without a program to aim toward. Money is tight.

Question 6. Have to do system studies to drive out system requirements.

Question 7. TIM - Yes, where or when?

SESSION II: ELA CONTROL ELECTRONICS

1. Assess ELA technology readiness as demonstrated by the performance capabilities of the Workshop prototype hardware. Has feasibility been definitively established?

2. Identify Critical Path elements on completing ELA Technology Bridging development by FY-95, considering:
   - ELA systems demonstrations (actuator/controller/power source)
   - SSME Technology Test Bed (TTB) hot fire demonstration
   - a mechanism for NASA & Industry to down-select candidate ELA systems for TTB
   - special emphasis on EMI

3. Discuss the utility of a NASA ELA System Design Handbook as an output from ELA Technology Bridging.

4. Assess the vitality of Industry supported ELA prototype developments; will NASA support be <u>necessary</u> ?

5. Assess the pros & cons of ELA technology fly-offs under ELA-TB, including
   - Permanent Magnet vs Induction Motors
   - PWM vs PDM
   - Analog vs digital vs hybrid electronics
   - IGBTs vs MCTs

6. Recommend the format for the next ELA TIM/Workshop/Conference: WHAT, WHEN & WHERE.

SESSION II: ELA CONTROL ELECTRONICS

October 1, 1992

Question 1. Feasibility has been established, but full power level has not been demonstrated. Before full power can be demonstrated the following issues must be resolved:

a. EMI must be addressed
b. Packaging of power devices (Air Force is currently working on packaging)
c. Motor optimization
d. Flight current sensors
e. Single event upset
f. Start transients
g. Batteries.

Question 2. FY 95 is feasible if funding and above questions are answered.

- Must identify (EMI, performance, etc.) requirements and specifications.
- In order to meet FY 95, there must be cost sharing between government and industry.
- On TTB hot fire demonstrations, a common TTB requirement for all vendors is needed.
    a. Is TTB our most effective/realistic test?
    b. Does it simulate flight profiles?
    c. Could performance requirements be full demonstrated at vendor facilities?
- Each company should be allowed access to TTB/test fixture.
- Government splinter session recommendation is demonstration at a common test facility.

Question 3. NASA ELA System Design Handbook is not recommended. A system requirements and specification document is preferred.

Question 4. Program Office should show time and hardware commitments for ELA hardware. Recommend cost sharing and Cooperative Research Agreements.

Question 5. Fly-offs should not be required. Requirements should be to meet performance requirements at full power. System design should not be a factor, rather system requirements.

Question 6. Next ELA meeting should be a full power demonstration (approximately 1 year from now with location yet to be selected).

SESSION III: ELA POWER SOURCE SYSTEMS

1. Identify the critical PSS parameters/requirements which need to be provided by ELA designers in order to "optimize" the combined ELA/PSS systems.

2. Outline the means by which NASA's ELA Technology Bridging can elicit these requirements,

3. Identify any specific ELA (performance) requirements that would distinguish ELA PSS developments from other, related PSS developments, such as DOE and automobile manufacturers.

4. Discuss the utility & implementation of an ELA-TB consignment unit for PSS prototype development:
   - a programmable IGBT-based power load with power-demand profiles
   - a "portable" ELA test unit (Motor/controller/geared loads, etc)
   - power profiles to simulate worst case flight trajectories & launch pad checkouts (steps, slews, FRFs, et

4. Discuss the utility & implementation of an ELA-TB Power Source Simulator for PSS prototype development:
   - generation of analytical models for a programmable Power Source Simulator
   - protection of proprietary data in supplying such data (eg, a floppy disc data transfer with execute-only

5. Sketch a Timeline of related Power Source technology development with respect to:
   - ELA - Technology Bridging with a completion date in FY-95.
   - early HLLV ELA systems to support a CY-96/97 launch

6. Recommend the format for the next ELA TIM/Workshop/Conference: WHAT, WHEN & WHERE.

C-8

ELA-TB WORKSHOP
ELA POWER SOURCE SYSTEMS
SPLINTER SESSION OUTPUT

QUESTIONS 1 & 2:

The PSS parameters/requirements needed by both NASA's ELA Technology Bridging Team and PSS vendors for definition and design are as follows:

- Power profiles which include; base power, voltage limits, peak power, total energy, rise times, regulation requirements, and frequency/spacing of current pulses.

- Start transient loads.

- Ascent profiles/worst case scenarios from Flight Dynamics area.

- Corona and EMI Specs and allowances.

- Redundancy and reliability numbers.

- Failure modes.

- Environmental requirements, acoustics, vibration, thermal, etc.

- Processing , handling, shelf life, pad access, and activation.

- Regeneration tolerance.

- Propellant availability.

- Pre-launch check-out, start-up times, GSE availability and use.

- Load impedances.

- Data and documentation expected from vendors.

Question 3:

ELA PSS requirements that are specifically ELA demands include; launch/flight environments, high current spikes, high voltage, and rise times.

Question 4:

The implementation of an ELA-TB consignment unit for PSS development was decided to be non-advantageous to NASA ELA-TB.

Question 5:

The development of a power source simulator is a good idea. This type project is currently underway with JSC's ELAPSS project.

Question 6:

A credible timeline can not be generated until more Power Source requirements are defined.

Question 7:

The Feb/Mar time frame was decided upon for the next ELA-TB TIM. Requirement updates and technology advancements should be the main topics for the Power Source Systems session.

SESSION IV: ELA OPERATIONS

1. Outline the means by which ELA operational requirements may be identified under ELA-Technology Bridging and ultimately translated into CEI specifications.

2. Discuss the means to effective utilize an ELA Operations Test Bed at KSC, including
   - use of NASA and Industry consignment units
   - pros & cons of focusing on a specific mission/application (SRM/ASRM aft skirt)

3. Assess the requirements, pros & cons of an ELA-TB sponsored development of a GSE-CART unit (BIT, power source simulator, ground handling & installation, etc)

4. Assess the NASA need, and the commercial/industry technology readiness, to support SSC/KSC/MSFC/JSC cryogenic flow control operations.

5. Recommend the format for the next ELA TIM/Workshop/Conference: WHAT, WHEN & WHERE.

SESSION IV. ELA OPERATIONS

October 1, 1992

OBJECTIVES - **CONCURRENT ENGINEERING**

* Need a representative hardware platform to drive out real operational requirements and prioritize.

* Need operation environment for:
  - Feedback to designers (and researchers)
  - Safety design feedback
  - Realistic timelines
  - Validate/recommend changes to prototype OMRSD/LCC.

* Near term/mid-term/long-term approach to concurrent engineering.

IMPLEMENTATION

Two pronged approach:

1. Form process improvement and design improvement teams.

2. Consider utilizing SRB AFT skirt as platform to meet the objectives.

Organization

Solid Rocket Booster TVC Group		
TEAM	***CHARTER***	***TEAM COMPOSITION***
Processing Improvement Team	To take action to reduce ***remanufacturing and processing task durations, man-hrs and IPR/PR count*** of the Solid Rocket Booster's thrust vector control system by **25% in 24 months.** Also, recommends any needed OMRS changes, vehicle design changes (large, medium and small), and retrofit approaches as **coordinated with the *Design Improvement Team.***	NASA MSFC/EE11 NASA Flt Ctls/TV-GDS-22 NASA APU-Hyd/TV-FSD-21 USBI-DAE/TO-1 LSOC Flt Ctls/LSO-215 LSOC APU-Hyd/LSO-356 *Design Sponsors:* 1. MSFC Propulsion Lab 2. USBI/MSFC
Design Improvement Team	To take actions needed to **modify the SRB TVC system** such that a **25% reduction within 48 months (and another 25% within 96 months)** occurs in the following areas: **1. Aft Skirt TVC Build-up & ACO** **2. Veh Processing Task Durations** **3. Man-hrs** **4. FMEA/CIL count** **5. LRU/SRU count** **6. Logistics *recurring* costs** **7. GSE count** The Design Team will **coordinate and reach agreement with the Processing Team** on all design modification and retrofit strategies. The Design Team will also aid the Processing Team on recommendations for OMRSD improvements.	NASA MSFC/EP64 NASA MSFC/EL NASA MSFC/EB RIC-DNY/APU-Hyd *Processing Sponsors:* 1. NASA Flt Ctls/TV-GDS-22 2. NASA APU-Hyd/TV-FSD-21 3. USBI-LSS

SESSION V: ELA REDUNDANCY & HEALTH MANAGEMENT

1. Assess the state-of-the-art and technology readiness level of Health management systems in supporting ELA-TB development by FY-95, including
   - Built-in-Test
   - Redundancy Management
   - Vehicle Health & TVC subsystem Health Management

2. Assess the redundancy management levels/capabilities/limitations of ELA prototype systems as demonstrated at the Workshop, including:
   - three channel EHA actuator (Boeing/Allied Signal)
   - eight channel Permanent Magnet EMA (Honeywell)
   - three channel Permanent Magnet EMA (Allied Signal)

3. Discuss the means to effective utilize an ELA/TVC Health Management Test Bed at MSFC/JSC, including
   - use of NASA and Industry ELA prototype systems (actuators & power source)
   - protection of vendor proprietary data/software in a NASA test bed

4. Assess the vitality of Industry/IRAD health Management development w.r.t ELA/TVC systems; will NASA support be mandatory?

5. Recommend the format for the next ELA TIM/Workshop/Conference: WHAT, WHEN & WHERE.

ELA REDUNDANCY & HEALTH MANAGEMENT SPLINTER SESSION

Don Brown/NASA JSC

1 October 1992

OBJECTIVES:

- Identify technology requirements associated with ELA redundancy management (RM) and health management (HM) and those areas that represent a potential high return on investment for Bridging Program funds.

  Technology shortfalls
  Technology demonstrations
  Tools and other support requirements

  What cost : benefit metrics can we identify?

- Define the interfaces between ELA RM & HM and overall Integrated Vehicle Health Management (IVHM).

- Identify proper relationship(s) between the following technologies/disciplines:

  Design for Testability
  BIT/BITE
  Boundary Scan
  Smart Sensor technology insertion options
  Sensor reduction/elimination (i.e. commutation support sensors)

- Discuss recommended NASA approach to fault tolerance and RM for actuators.

  i.e. should a single EMA be used in a flight critical application?

  What guidelines should drive selection of actuation technology, i.e. EMA vs. EHA, PM DC vs. induction, etc.?

- Identify white paper products that would be valuable:

EMA vs. EHA selection considerations and criteria
Motor selection
Failure recovery approaches (i.e. lock-up vs. return to null)

PARTICIPANTS

MDSSC - Delta Launch Vehicle EMA
Univ. of Alabama - characterize roller screws and ball screws
R A Weir MSFC CDL
Aerojet
LeRC
LaRC - GN&C avionics I/F
Allied Bendix
Moog Boeing NLS TVC
Jack B NLS
Bill St. Cyr SSC
Fred H.

Good x-section of disciplines and interests.

APPROACH

Answer J Sharkey questions.
Identify significant omissions.

ELA requirements id and collection mechanism required. Support immediate term, through demos, to long term. MSFC ELA requirements QFD (joint team in place). Focus is on NLS. Target completion by February 1993.

****
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Q1

Subsystem level maturity is good - global strategies and tools are still lacking. Integration of technologies is not mature; the technology elements are.

White papers. Concentrate on the way we do fault management. Concern on what audience would be. ELATB would collect, catalog and publish. Don will generate a list of potential targets.

Standalone versus "cooperative" VHM approaches.

NLS says need integrating glue to transition from health monitoring to IVHM. Elimination of unnecessary sensors; use data captured in normal control signals, etc. LeRC has started this effort (university supported study); would use excess controller processing power.

Realistic failure analysis/fault tree data required. - Follow up to Rae Ann's data.

FOUR TRACKS FOR IVHM DEVELOPMENT

ARCHITECTURE
FLIGHT SUPPORT SYSTEMS (GROUND/FLIGHT)
TOOLS

ELA TECHNOLOGY is ready now - Boeing. Architectural decisions will drive subsystem design philosophies. Work is required to tie operations and development together. NLS says smart sensors have option to do processing at lowest level but there must be reporting to a central level to support launch processing, flight control. Local analysis with avionics suite for coordination. This seems to be a uniform approach.

FDIR and data requirements are different for ELV Vs reusable.

How much reliability is needed? Tied to human rating issues.

Q2

Boeing/Allied EHA - advantages of hydraulic bypass are undeniable. Fail op/fail safe (return to null). No real RM demo has been offered yet. How far down must we take redundancy? Should rotor shafts and bearings be considered? What are credible failures? Up front involvement of R&QA needed.

For 8 channel, they have had several failures and the system continued to run. This is really used as a 4 channel device. The motor shaft is common to all.

Trade between redundancy content and HM.

Q3

MAST approach is to not allow proprietary content. To date, there have been no proprietary issues associated with ELA TB. Use of vendor/contractor facilities and capabilities as appropriate is desirable (in fact, mandatory). Networking of facilities would be valuable and cost effective to support specific end-to-end test objectives.

Would ELAPSS be a good asset for the CDL? There is not a problem in getting power for actuators (batteries, power supplies). The ELAPSS will never obviate final integrated system test requirement, however.

Facility here will continue to be a place we use to demo items. Proprietary issues should not be a problem. Do we need to address EMI/EMC issues? Can ELAs and avionics devices share the same power sources? Group seems to feel no.

Q4

Budgets are universally slim and getting slimmer. This includes IRAD funding as well. Question exists as to where resources will come from to "customize" ELA development to date to conform to desired architectures and IVHM requirements. NLS seems to be the only "carrot" out there. Maybe we should let aircraft people take (or maintain) the lead for ELA development.

TTB I/F would be a good demo to "sell" ELA capabilities since we are essentially proposing a replacement of something that does work.

Q5

Papers and demo mix was good. Recommend continued emphasis on demos in future TIMs and other forums.

Avoid having meeting span fiscal year transition!

SESSION XII

ELA PROTOTYPE DESIGN AND TEST RESULTS

MOOG INC.

MISSILE SYSTEMS DIVISION

38 HP ELECTROMECHANICAL ACTUATOR

IR&D PROGRAM OVERVIEW

NASA
ELECTRICAL ACTUATION
TECHNOLOGY BRIDGING
WORKSHOP

SEPTEMBER 29 - OCTOBER 1, 1992

INTRODUCTION

- Objectives of Moog's 38 HP EMA IR&D PROGRAM
- Design Criteria
- Hardware Description
- Test Results

OBJECTIVES

- Demonstrate EMA Performance for 30-50 HP TVC Application
- Design, Build, and Test Single String EMA Hardware
- Compare to Known Hydraulic System Performance
- Baseline SSME TVC Requirements
- Design Actuator To Accommodate
  - Ballscrew
  - Rollerscrew

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Missile Systems Division

PROGRAM PLAN

Initiated Moog Funded IR&D Activity 1990

- Demonstrate Single String EMA
- No Effort to Optimize Weight
- Include Dual Motor Capability
- Utilize "Bolt-On" Motors to Permit Motor Comparison
- Designed to Handle Start-up Transient Loads Structurally
- Controller not Flight Packaged

Future Considerations

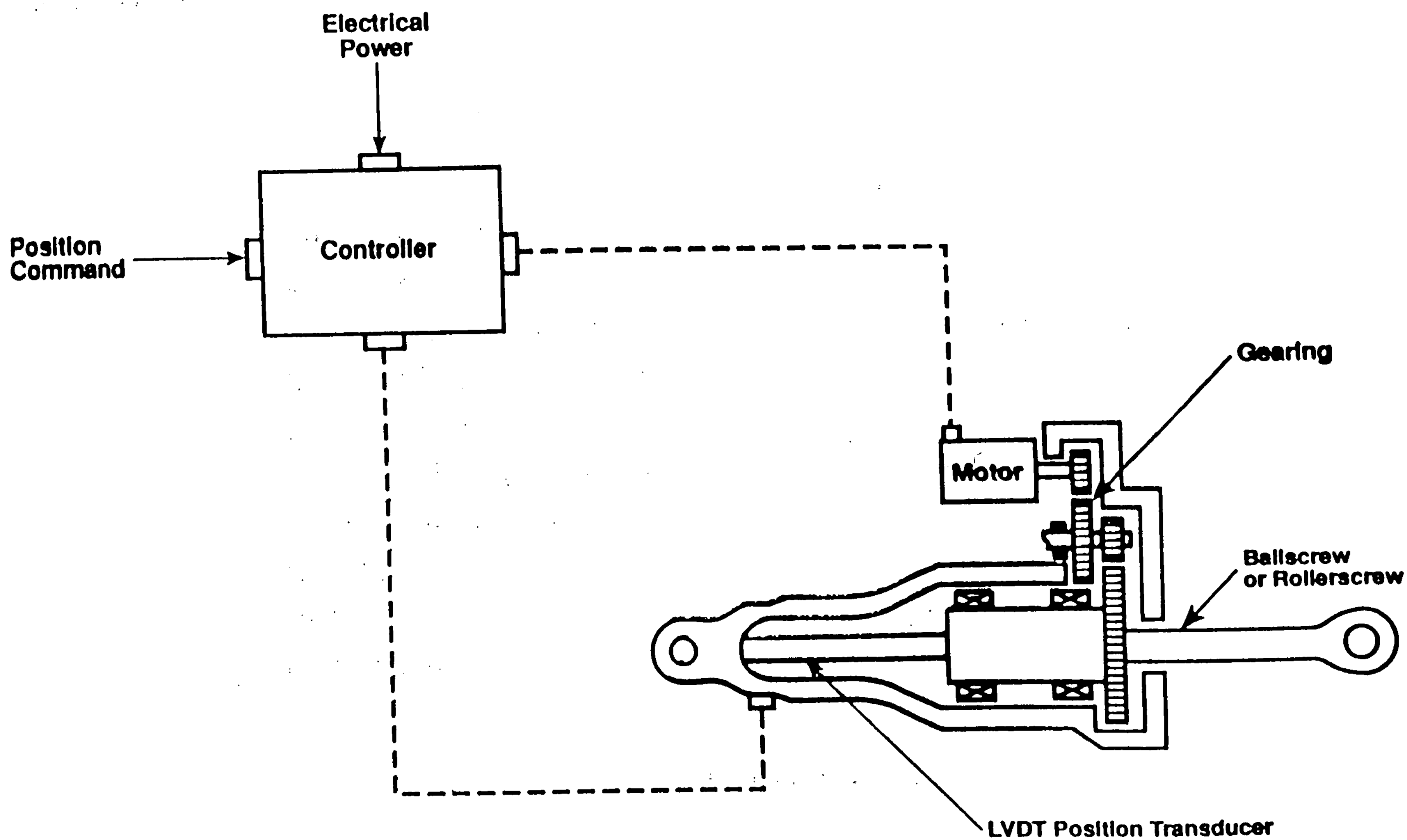
- Redundancy
- Impact Loads
- Motor Selection
- Power Source
- Flight Weight Controller and Actuator

DESIGN CRITERIA

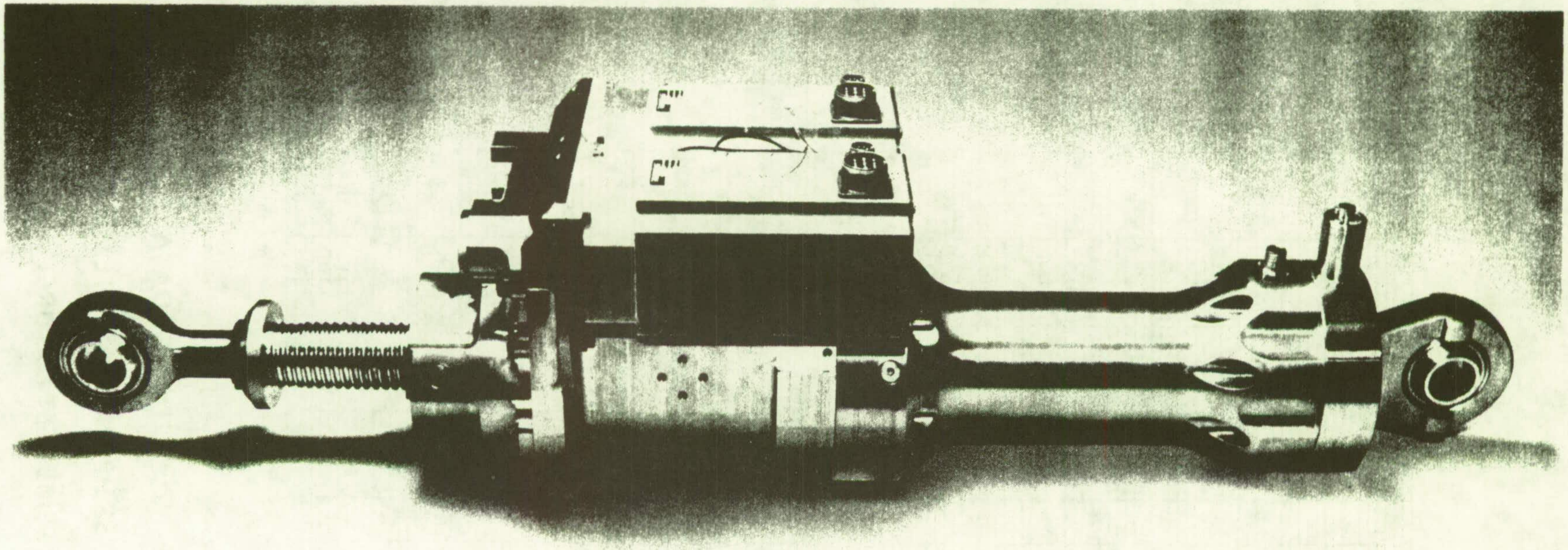
(Based on SSME TVC Requirements)

Supply Voltage	270 VDC
Output Travel	$\pm$5.5 in.
Rated Power	38 HP
- Output Force	48,000 lb.
- Output Velocity	5.2 in/sec.
Impulse Load Capacity	100,000 lb.
Frequency Response	
at $\pm$2% Command	<80 deg. phase at 3 Hz
Acceleration	60 in/sec^2
Pin to Pin Length	
at Mid stroke	47 in.

MOOG IR&D EMA TVC ACTUATION SYSTEM



MOOG

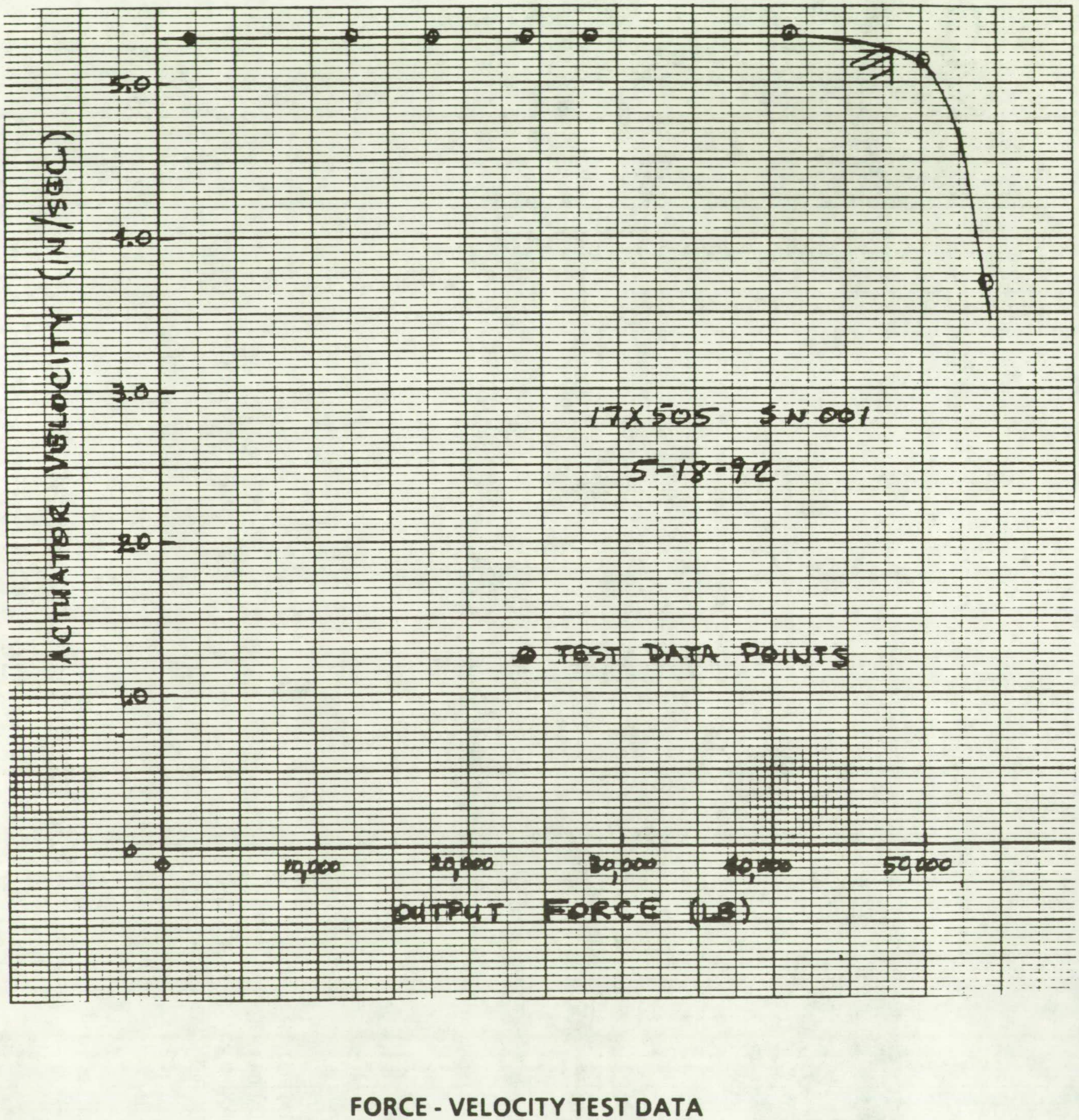


OUTPUT TRAVEL	±5.5 IN
STALL FORCE	48,000 LB
MAXIMUM IMPULSE LOAD	100,000 LB
ACCELERATION	60 IN/SEC^2

RATED POWER	38 HP
-OUTPUT FORCE	48,000 LB
-OUTPUT VELOCITY	5.2 IN/SEC
DUTY CYCLE	10 MIN
-AVERAGE LOAD	15,000 LBS
SUPPLY VOLTAGE	270 VDC

Electromechanical Actuator Dual Torque - Summed Motors

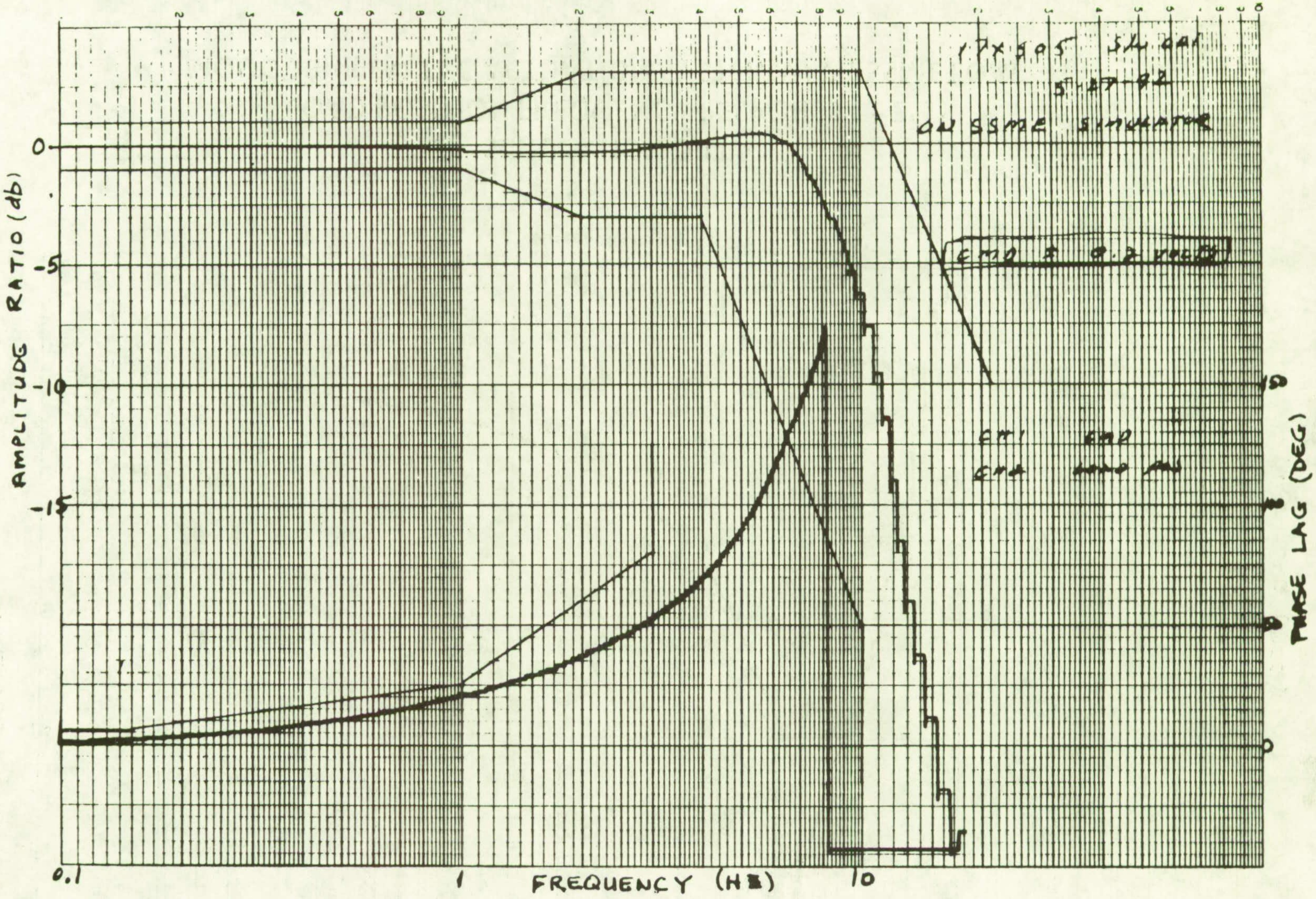
MOOG



FORCE - VELOCITY TEST DATA

MOOG 38 HP EM TVC SYSTEM

ON SSME TEST FIXTURE



TEST DATA

LOAD POSITION FREQUENCY RESPONSE (± 2% COMMAND)

MOOG 38HP EM TVC ACTUATION SYSTEM ON SSME SIMULATOR

MOOG

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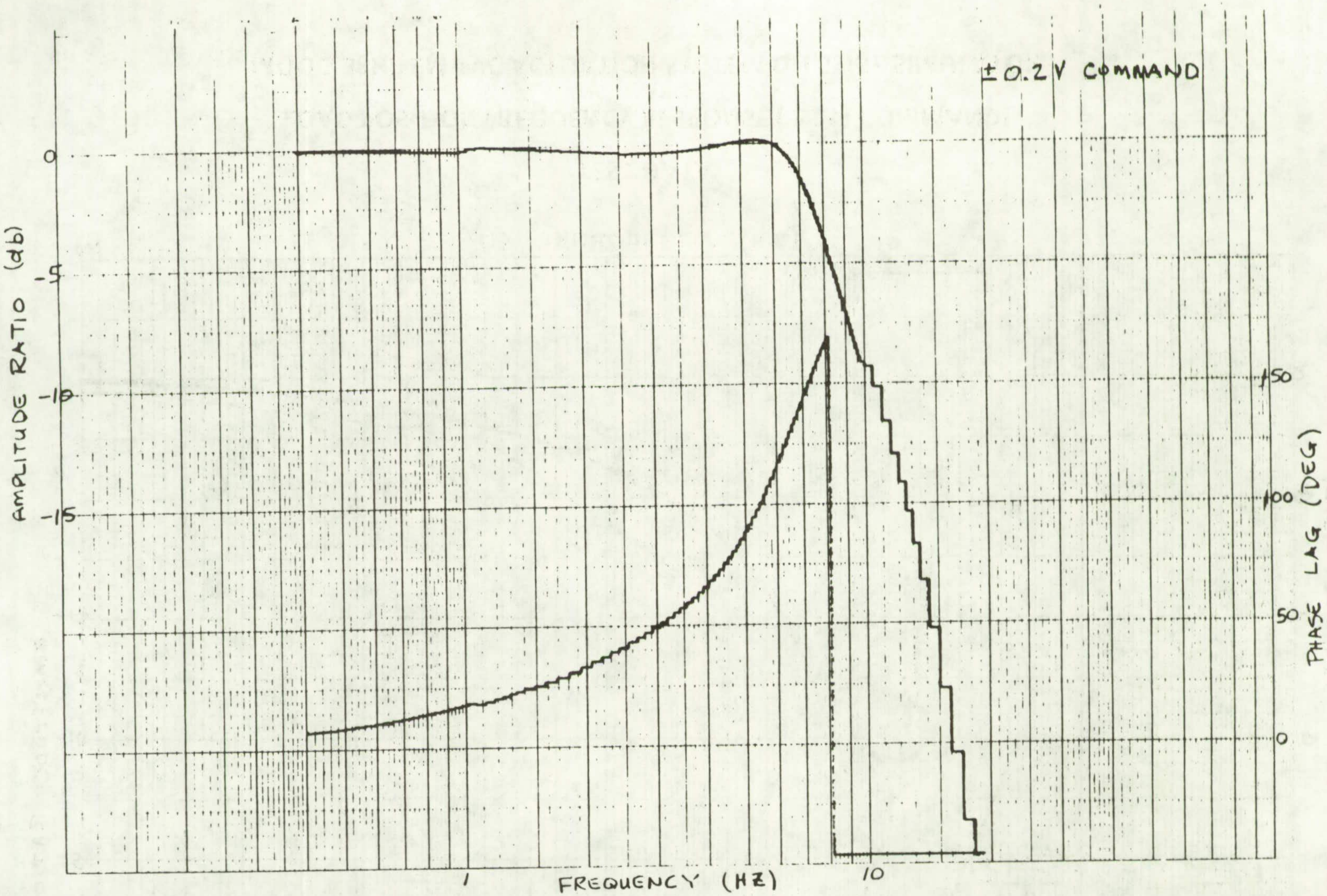
4-7-92.



SIMULATION DATA
LOAD POSITION FREQUENCY RESPONSE (±2%)
MOOG 38HP EM TVC ACTUATION SYSTEM WITH SSME LOAD

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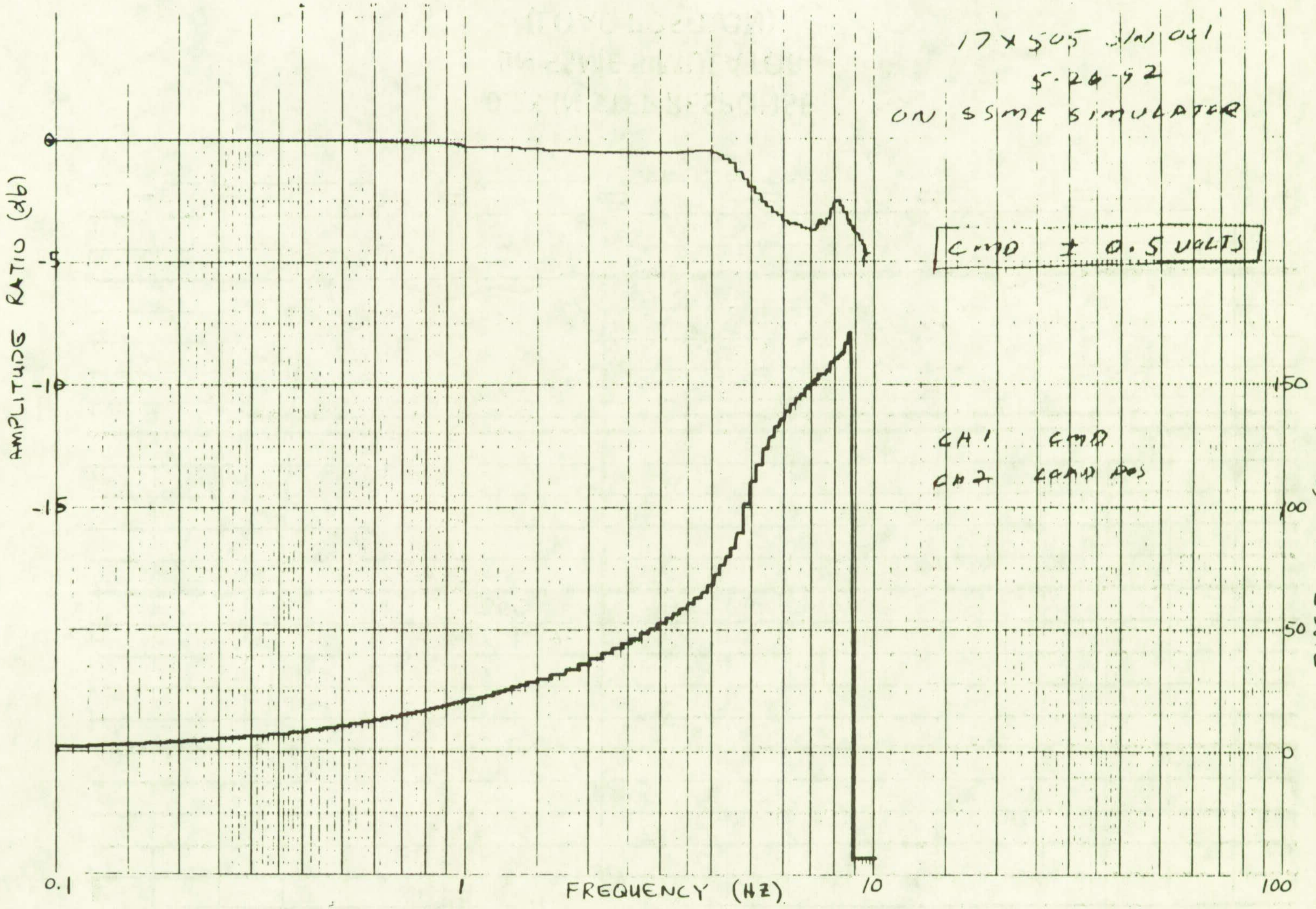

TEST DATA
LOAD POSITION FREQUENCY RESPONSE (±5% COMMAND)
MOOG 38HP EM TVC ACTUATION SYSTEM ON SSME SIMULATOR

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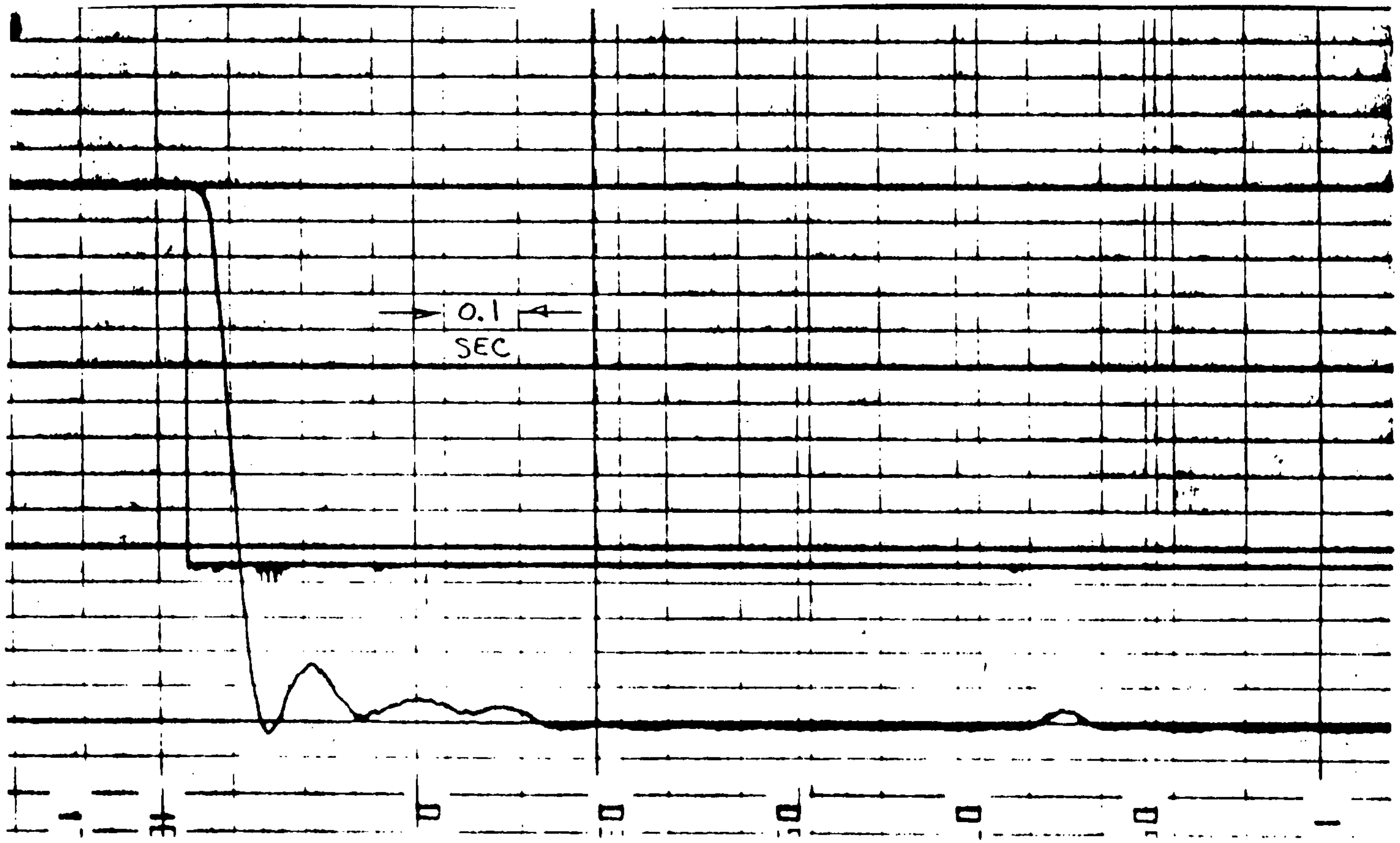
MOOG

694

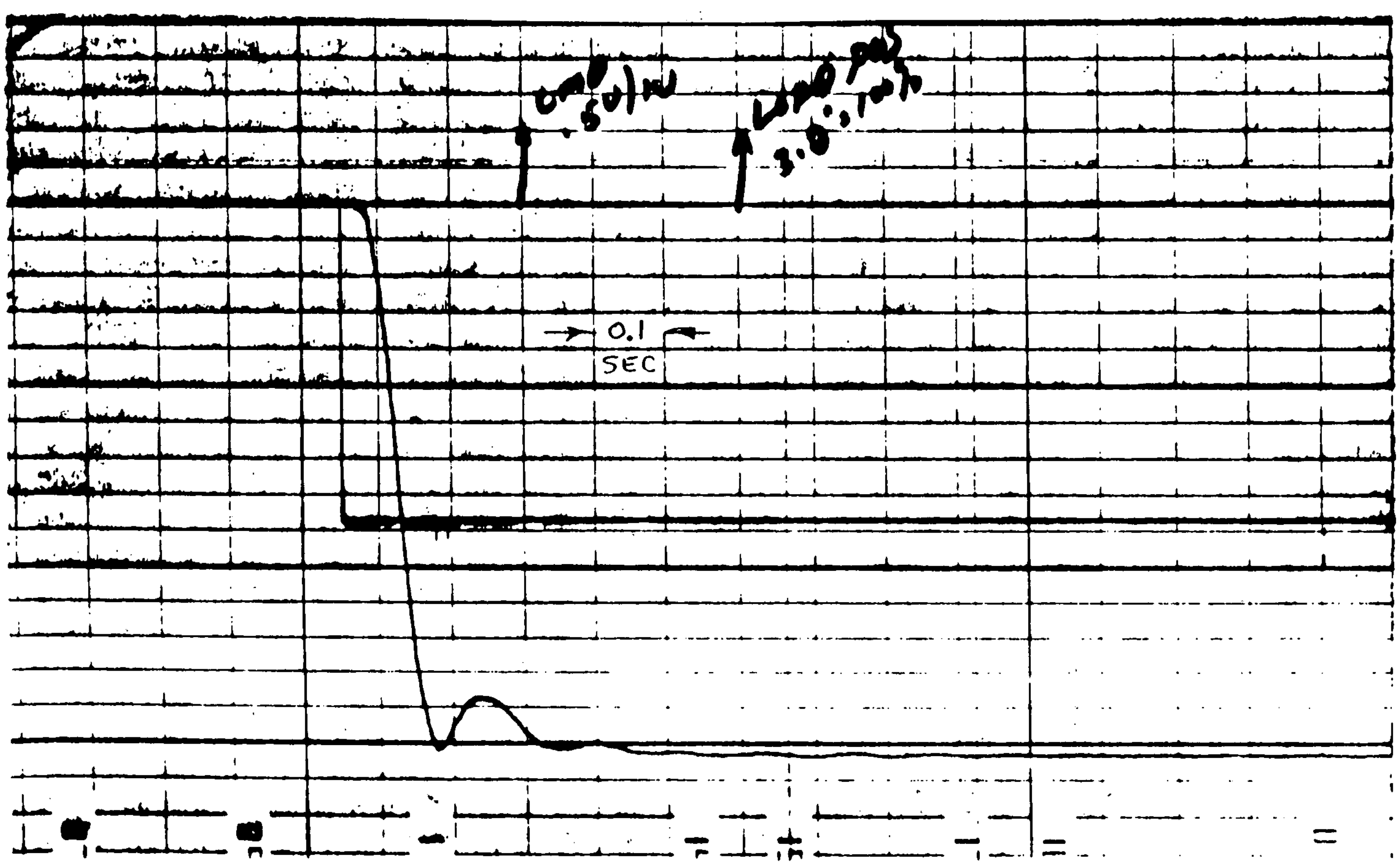
17E505 S/N 001
7-17-92



0.25 IN STEP RESPONSE
0N SSME SIMULATOR
(LOAD POSITION)

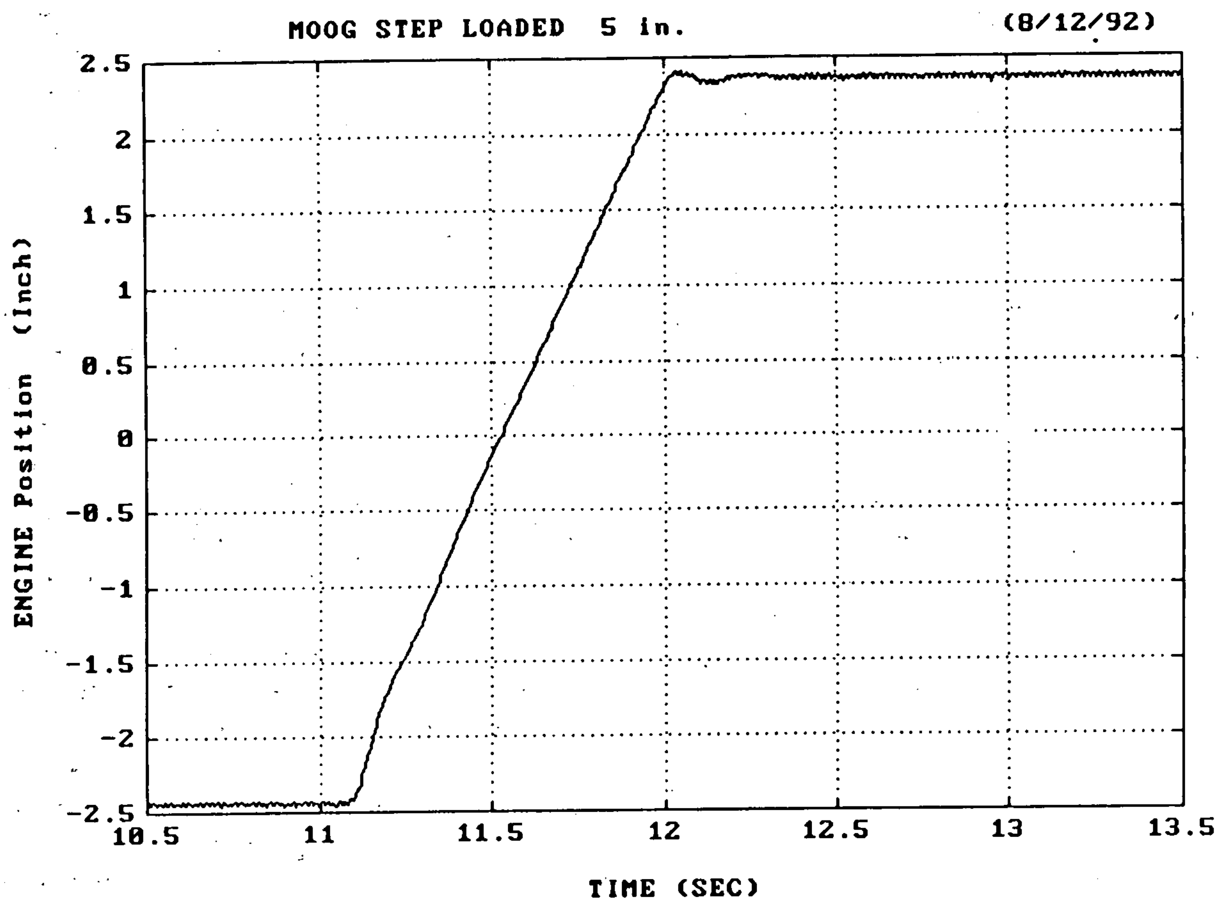
MOOG

17E505 S/N 1
7-17-92



**0.5 IN STEP RESPONSE
ON SSME SIMULATOR
(LOAD POSITION)**

MOOG



5 IN STEP RESPONSE
MOOG ACTUATOR ON MSFC SSME SIMULATOR

EM TVC ACTUATOR TEST DATA

	BALLSCREW ACTUATOR	ROLLERSCREW ACTUATOR
Mechanical Efficiency		
at Stall	70%	61%
at Power Point	78%	71%
Friction	1650 lbs.	1500 lbs.
Stiffness (Locked Rotor)		
Midstroke	1.47×10^6 lb/in	1.5×10^6 lb/in
Extend	1.34×10^6 lb/in	1.38×10^6 lb/in
Acceleration		
One Motor	130 in/sec^2	
Two Motors (One Driving)	65 in/sec^2	

MOOG

PERFORMANCE RESULTS OF MOOG BRUSHLESS EM TVC SYSTEM

Parameter	SSME Spec	Test Results
Frequency Response ($\pm 2\%$ Command)	<25 deg. Phase at 1 Hz <80 deg. Phase at 3 Hz	Meets Requirement
Rated Power Point		Meets Requirement
Output Force	48,000 lbs.	
Output Velocity	5.2 in/sec.	
Output Travel	± 5.5 in.	Meets Requirement
Actuator Stiffness	790,000 lb/in.	Meets Requirement

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Missile Systems Division

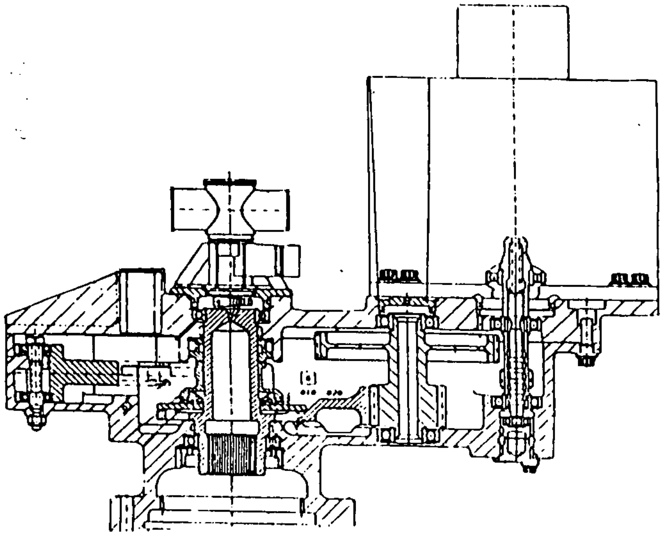
ELECTROMECHANICAL PROPELLANT CONTROL ACTUATORS

MARTHA B. CASH

EP\64

OCTOBER 1, 1992

ELECTROMECHANICAL PROPELLANT CONTROL ACTUATORS



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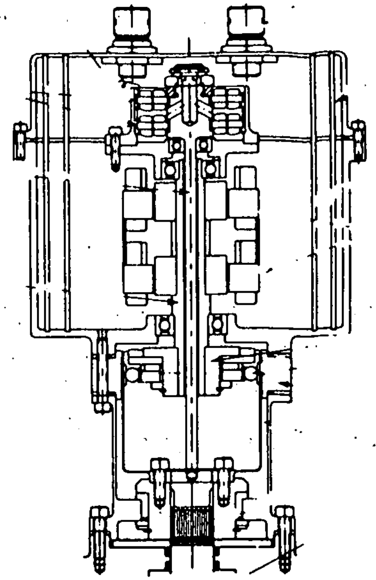
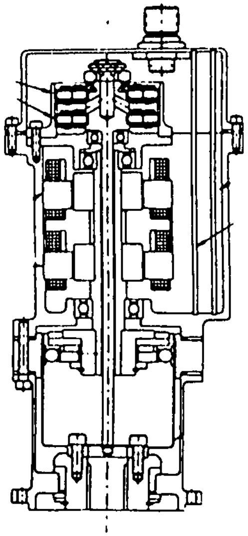
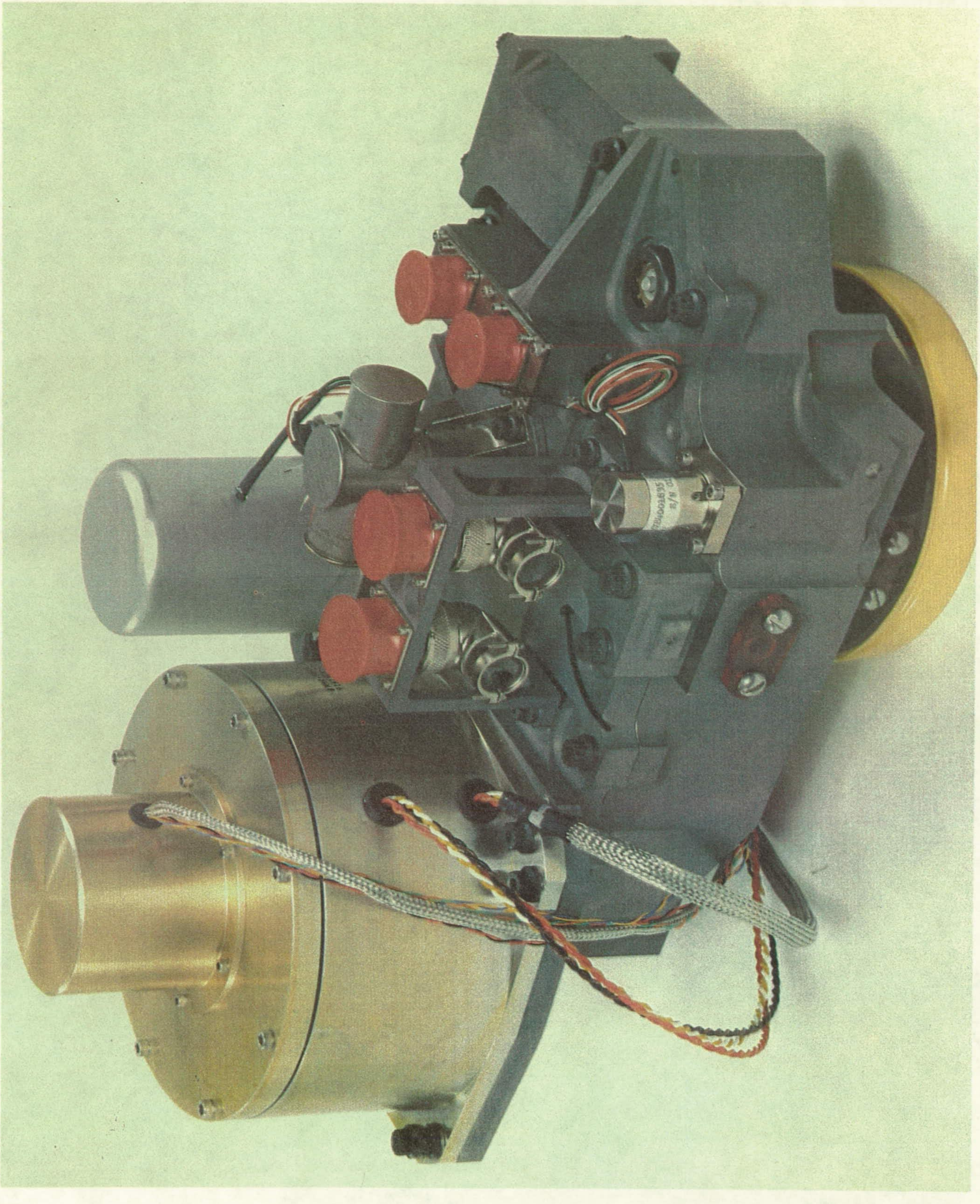


AEROJET



IIN-HOUSE SIMPLEX



MSFC AND TEXTRON SSME
PROPELLANT CONTROL VALVE
ACTUATOR

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COLOR PHOTOGRAPH

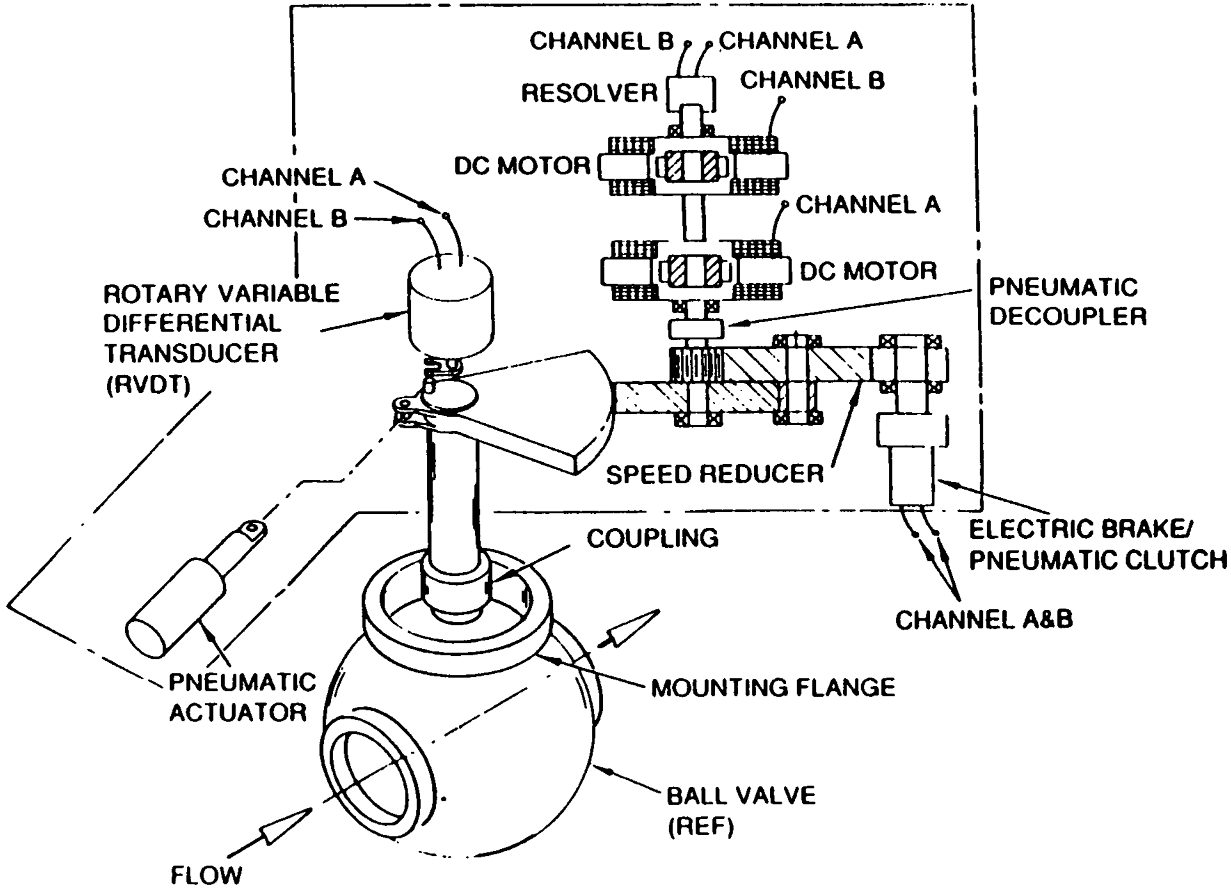


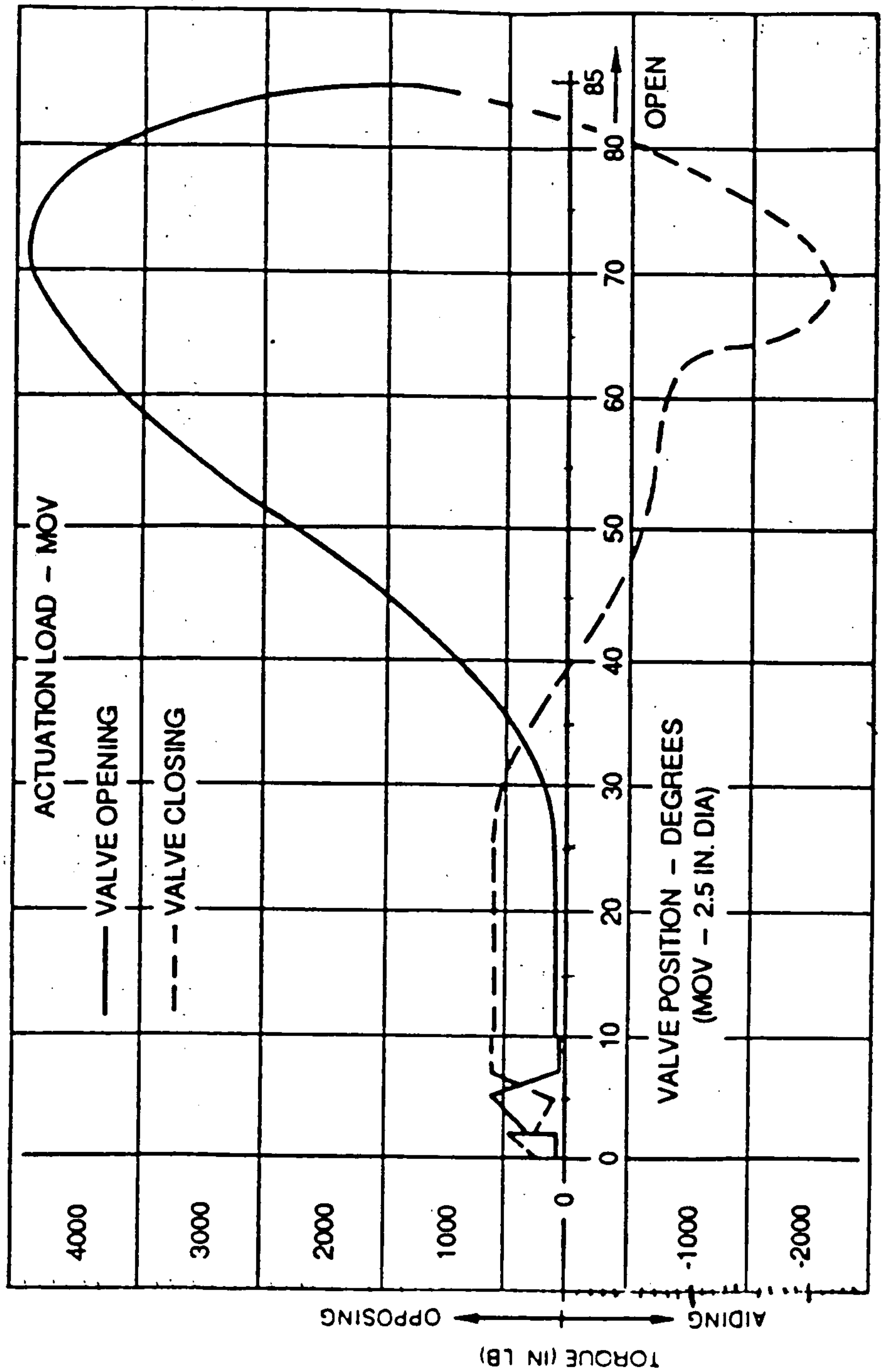
FIGURE 3
DUAL MOTORS WITH SINGLE-SHAFT CONCEPT

DESIGN REQUIREMENTS

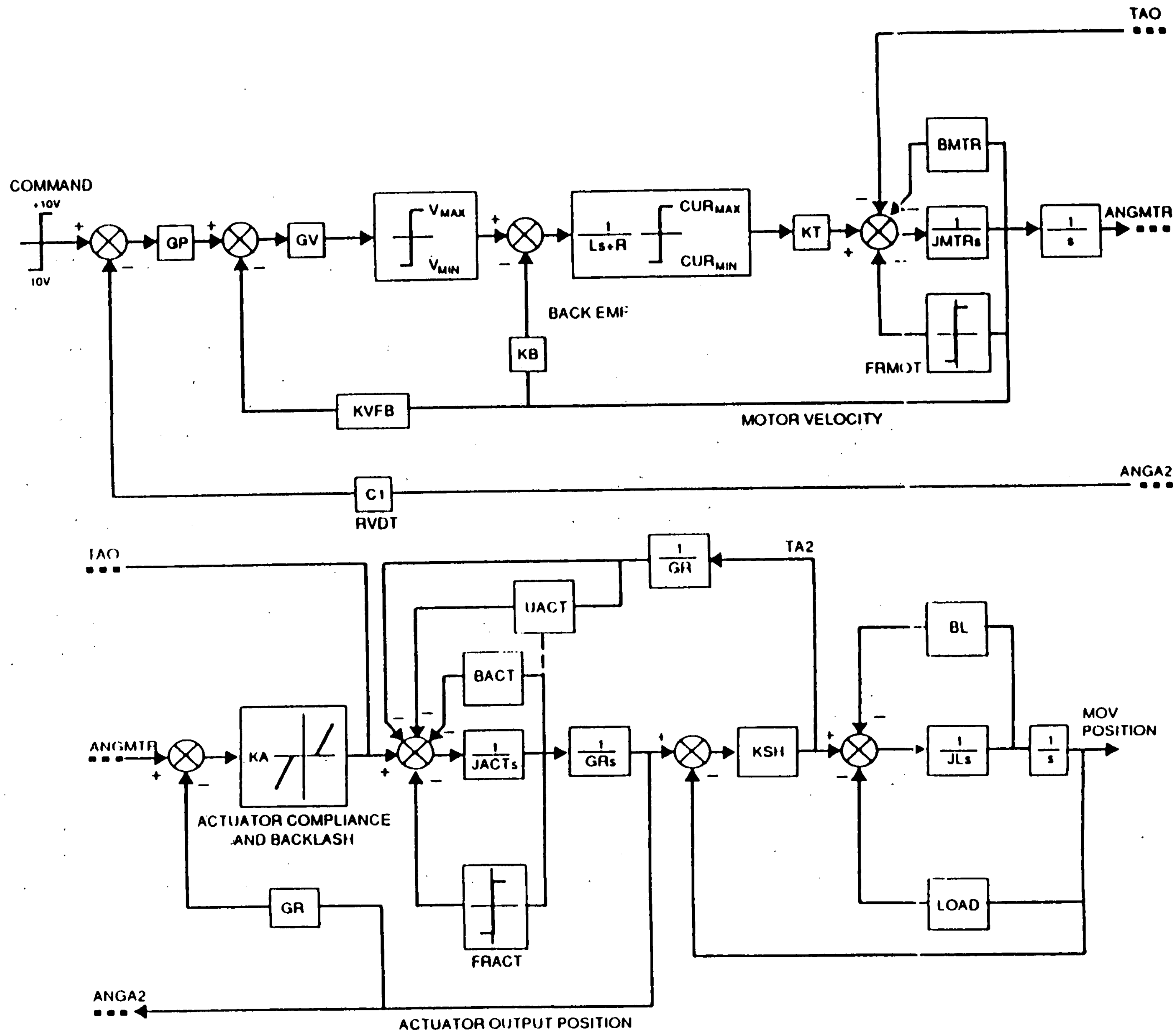
DESIGN REQUIREMENT	VALUE
VALVE OPEN/CLOSE TRAVEL	84° 45' - 85° 30'
VALVE POSITION ACCURACY	± 3% OF 85° (MAX.) ± 1.3% OF TOTAL TRAVEL FROM 50-60% OPEN
VALVE RATE (DEG./SEC.)	360 (MAX.)
ATMOSPHERIC PRESSURE (TORR)	SEA LEVEL TO 1×10^{-7}
AMBIENT OPERATING TEMP. (°F)	-50 TO 130
ACTUATOR CONTROLLER AMBIENT OPERATING TEMP. (°F)	40 TO 110
ACTUATOR NON-OPERATING TEMP. (°F) FOR 2 HRS.	-200 TO 10
LIFE (HRS)	8
LOAD (MAX.) (IN.-LB.)	4500
WEIGHT (LBS.)	70

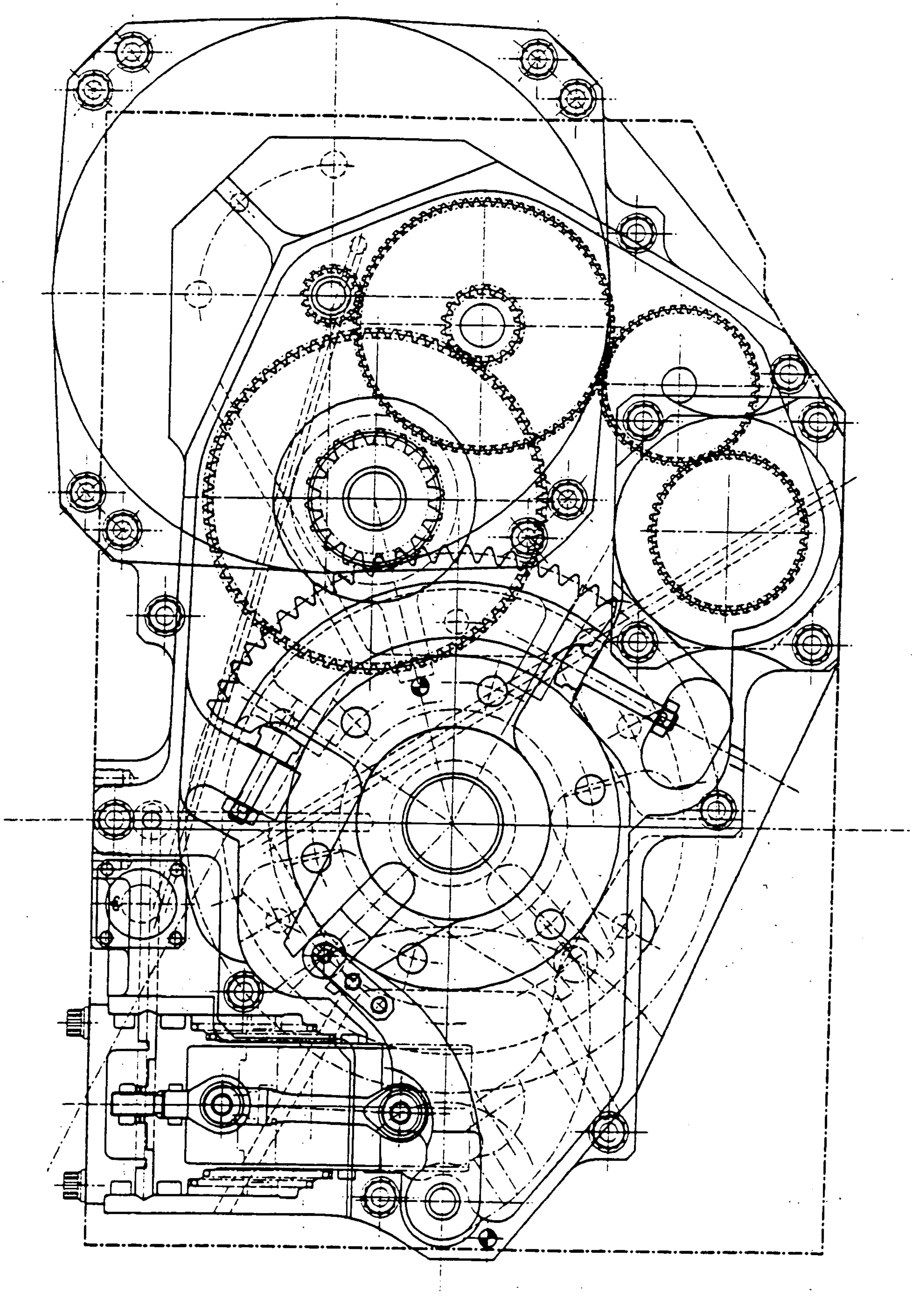
DESIGN PARAMETERS

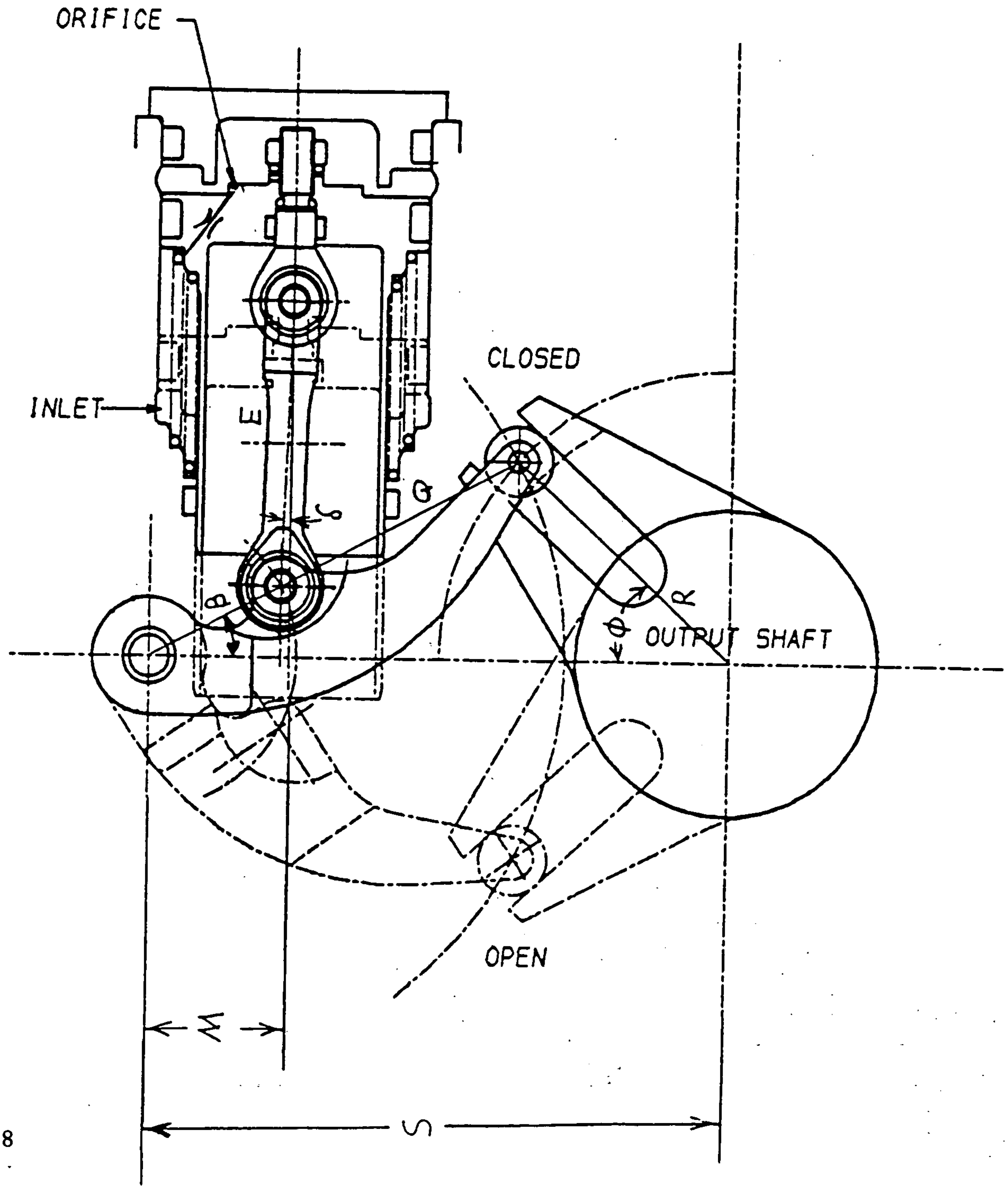
DESIGN PARAMETERS	VALUE
RVDT ERROR BAND	2% OF THE FULL SCALE
RVDT EXCITATION	20 VOLTS, PEAK TO PEAK AT 2000 Hz
GEAR RATIO	85:1
CLOSED LOOP THRESHOLD UNDER LOADING	0.025% OF FULL TRAVEL
MAX. CURRENT (AMP.)	40
LINE BUS VOLTAGE (VOLT)	270
VALVE RATE (DEG./SEC.)	245 (NOMINAL)
RESOLVER EXCITATION	4 VOLTS RMS PEAK TO PEAK AT 10 kHz
FREQUENCY RESPONSE	-3 db AT 10 Hz (NOMINAL) 90° PHASE LAG AT 10 Hz (MAX.)
ACTUATOR LOADING (IN.-LB.)	AS DEFINED IN FIGURE 1
HELIUM PRESSURE (PSI)	700 TO 800
PNEUMATIC SHUTDOWN VALVE CLOSING TIME (FROM FULL OPEN)(SEC.)	1.4 TO 3.1



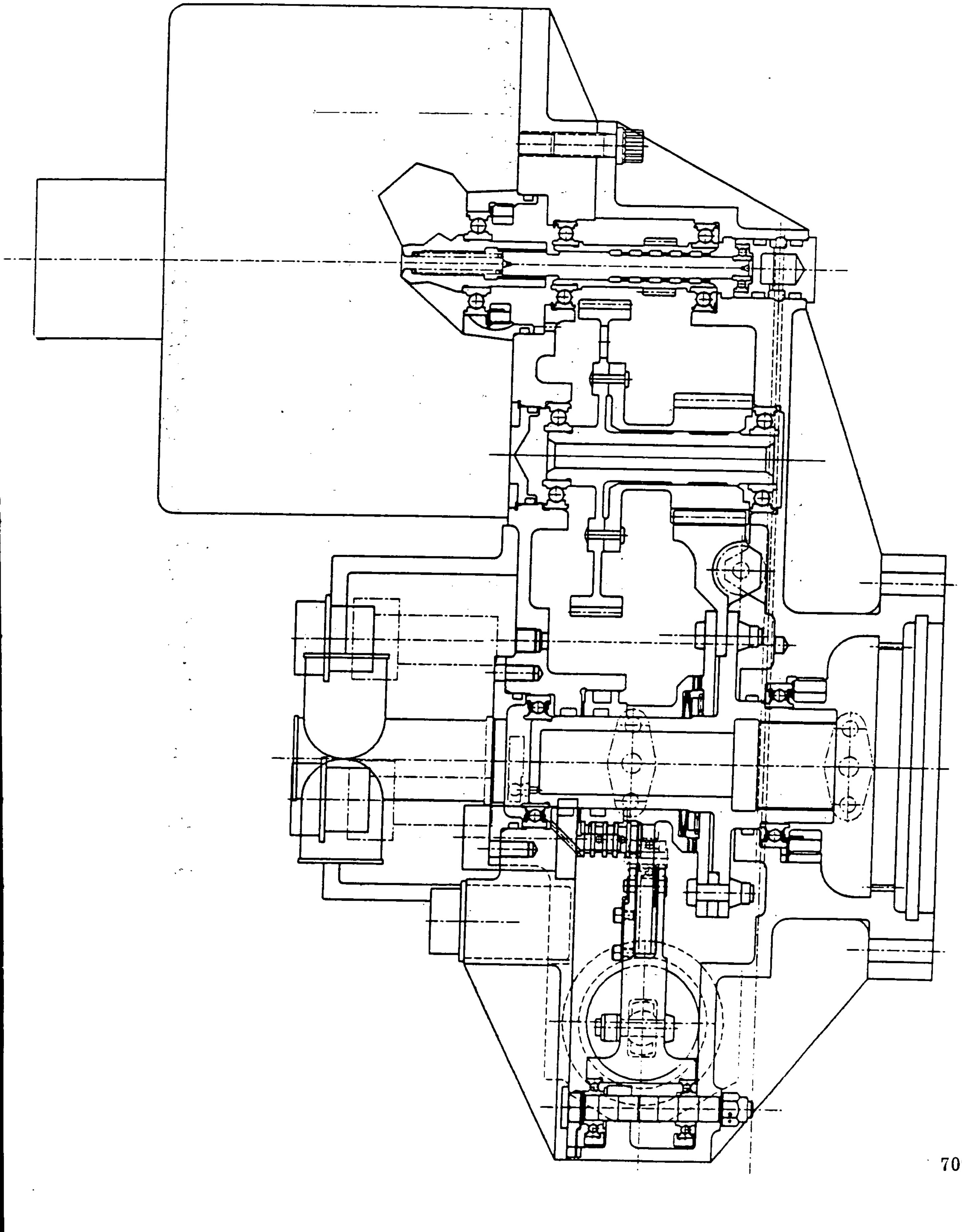
ACTUATION LOAD – MOV
VALVE OPENING
VALVE CLOSING
VALVE POSITION – DEGREES
(MOV – 2.5 IN. DIA)
OPEN
0
10
20
30
40
50
60
70
80
85
4000
3000
2000
1000
0
-1000
-2000
OPPOSING
AIDING
TORQUE (IN LB)

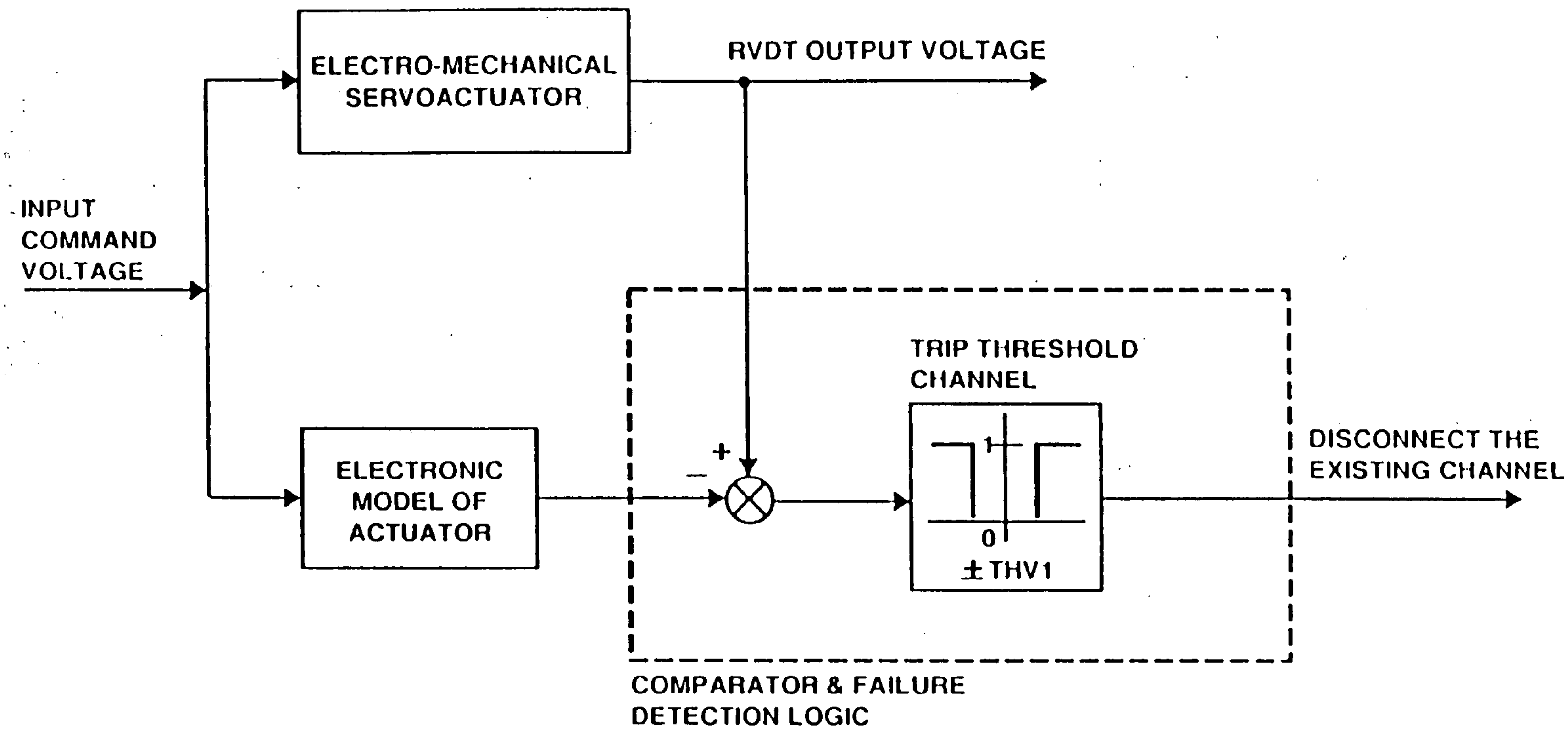

TAO
COMMAND
+10V
10V
GP
GV
V_{MAX}
V_{MIN}
$\frac{1}{Ls+R}$
CUR_{MAX}
CUR_{MIN}
KT
BMTR
$\frac{1}{JMTRs}$
$\frac{1}{s}$
ANGMTR
BACK EMF
KB
FRMOT
KVFB
MOTOR VELOCITY
ANGA2
C1
RVDT
TAO
$\frac{1}{GR}$
TA2
UACT
BACT
ANGMTR
KA
$\frac{1}{JACTs}$
$\frac{1}{GRs}$
KSH
BL
$\frac{1}{JLs}$
MOV POSITION
ACTUATOR COMPLIANCE AND BACKLASH
GR
FRACT
LOAD
ANGA2
ACTUATOR OUTPUT POSITION





MOV PNEUMATIC SHUTDOWN ACTUATOR





FAILURE DETECTION BLOCK DIAGRAM

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DOCUMENT NO. HR77700072

EXTENDED LOCKUP TEST (ATP para. 4.11.4)

P/N X41009110

Date SEP 1 5 1992 Operator HRT 148

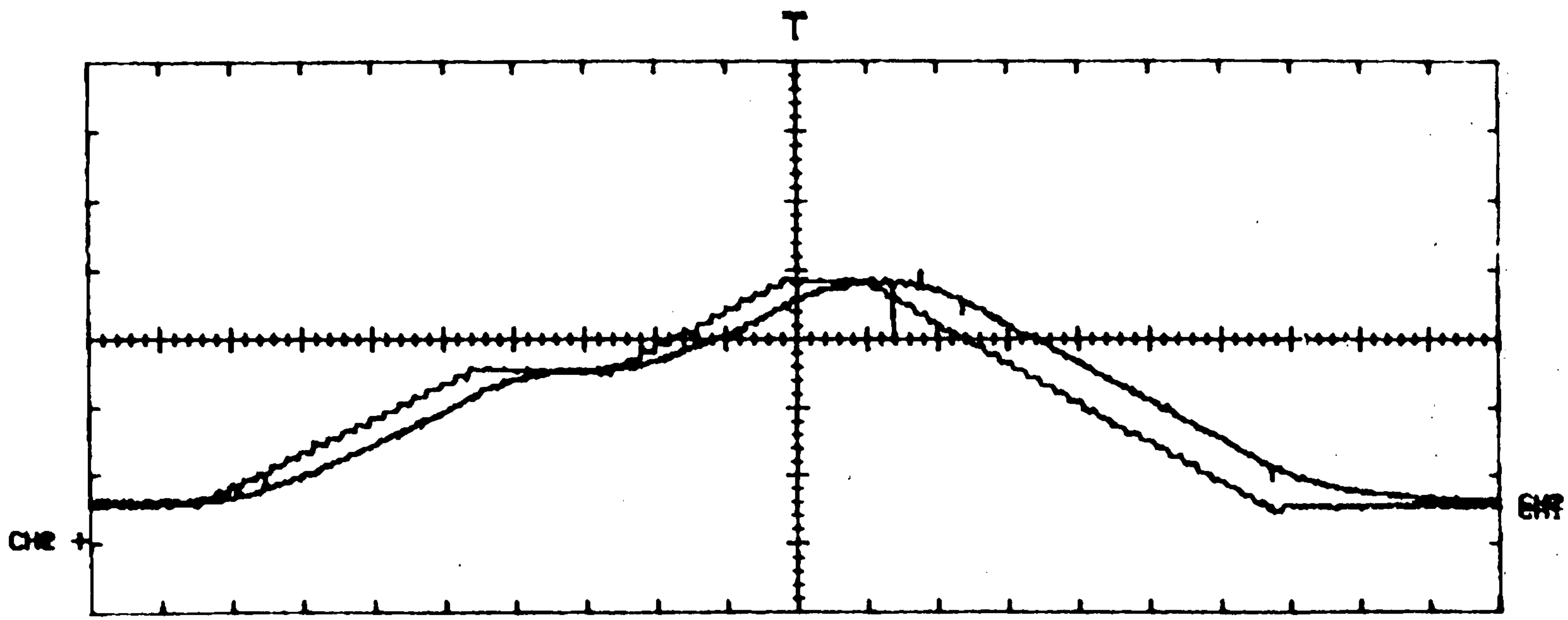
Comments Loaded

S/N X001

Item	Required	Actual
Load Direction Sense	CCW	CCW
Load	MOVA	MOVA
Reduced Power	Minimum	MIN
Encoder Reading (Start of Lockup	1894 ± 2 bits	1894
Encoder Reading After 10 Min Lockup	////////////	1846
Total Drift After 10 Min Lockup	82 bits max	48
Load Direction Sense	Active	ACTIVE
MOV Load	Remove	REMOVED

TEK/2430

	.C	2 V /div	NORMAL	100mSEC/div
CH2	DC	2 V /div	NORMAL	100mSEC/div



COMMAND TRACKING

Fin A Panel

P/N X41009110

S/N X001

SEP 16 1992

HRT 148

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DOCUMENT NO. HR77700072

ACTUATOR SLEW RATE (ATP Para 4.9)

P/N X41009110

Date SEP 1 5 1992 Operator HRT 148

Serial No. X001

Comments: Loaded

	Shaft Position	Input Signal	MFVA Load	Slew Rate %/Sec			
Required	Open-Close-Open	+30 ±1 mA	MOVA Load Fig. 11	143 min.			
	Open-Close-Close			340 max.			
(Failsafe Switch only Energized)	Close to Open	+30	Data Fig. 1	161 %/s			
	Open to Close	-30	Data Fig. 2	172 %/s			
(Failop and Failsafe Switch Energized)	Reversal to Closed	+30	Data Fig. 3	152 %/s			
	Reversal to Opened	-30	Data Fig. 4	157 %/s			

EG 056

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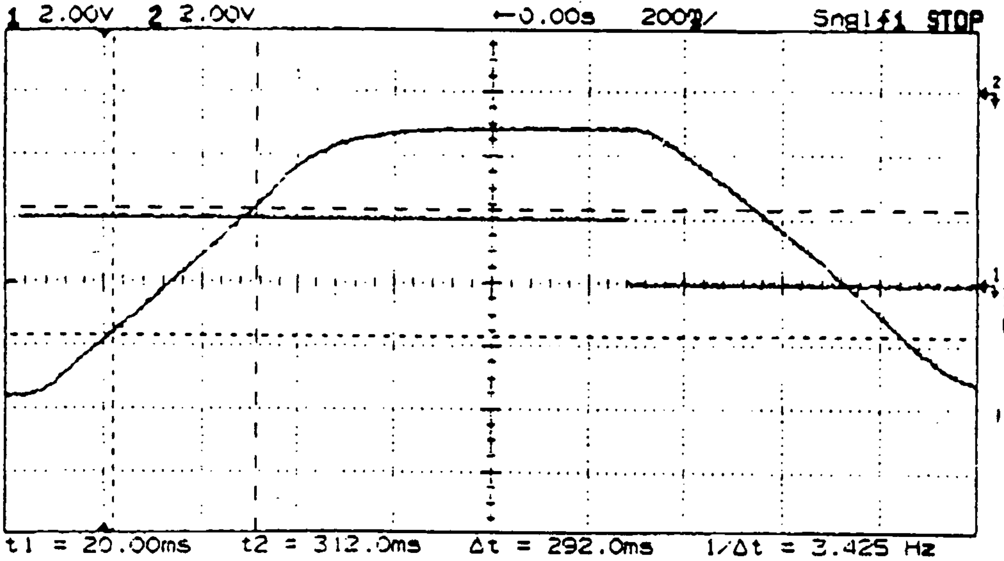
DOCUMENT NO. HR77700072

ACTUATOR SLEW RATE (ATP Para 4.9)

(Page 2 of 3)

P/N X41009110 S/N X001

SEP 15 1992

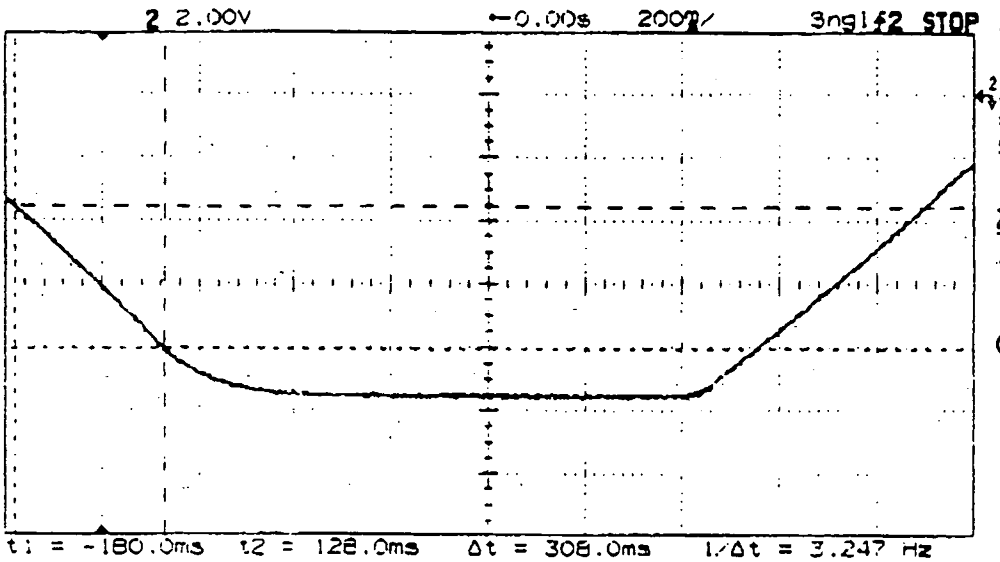


292 milliseconds

2.0 Vdc/div
ter output)

0.2 sec/div
(time)

TO OPEN



308 milliseconds

) Vdc/div
r output)

2 sec/div
me)

CLOSED

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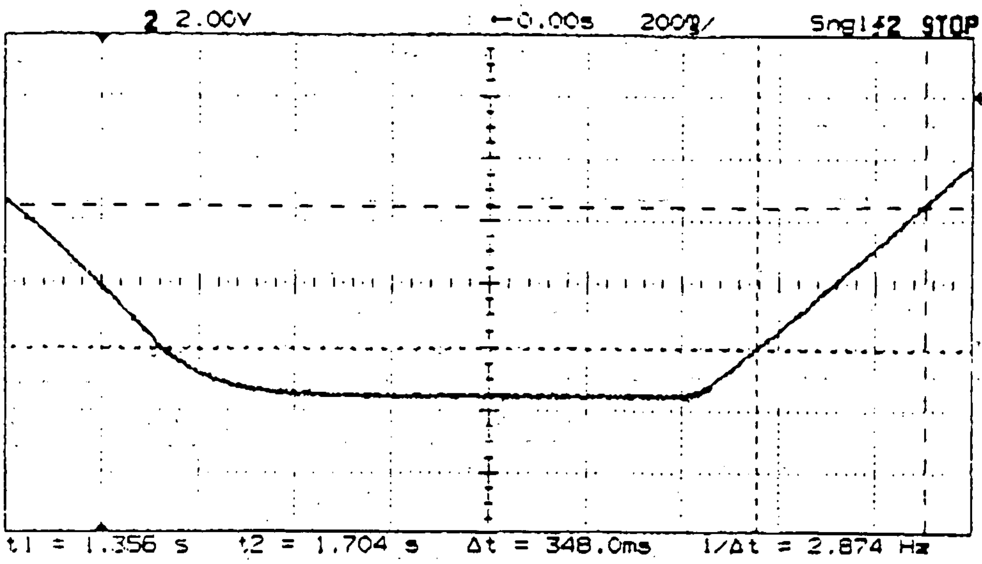
DOCUMENT NO. HR77700072

ACTUATOR SLEW RATE (ATP Para 4.9)

SEP 15 1992

HRT 148

P/N X41009110 S/N X001



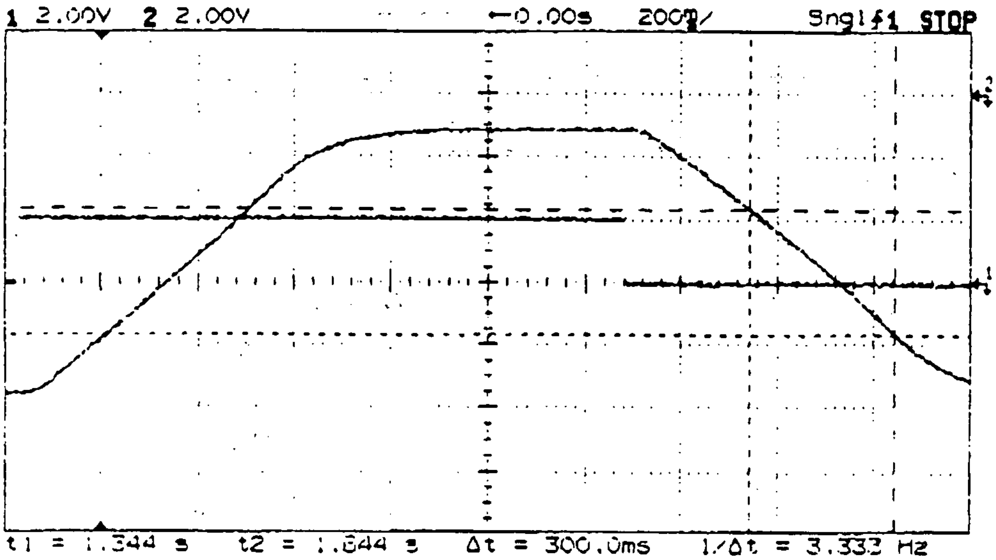
348 milliseconds

_______ Vdc/div
output)

_______ sec/div
ne)

) OPEN

300 milliseconds



_______ Vdc/div
output)

_______ sec/div
:)

OSED

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DOCUMENT NO. HR77700072

PNEUMATIC SHUTDOWN DATA SHEET (ATP Para 4.11.3)

P N X41009110

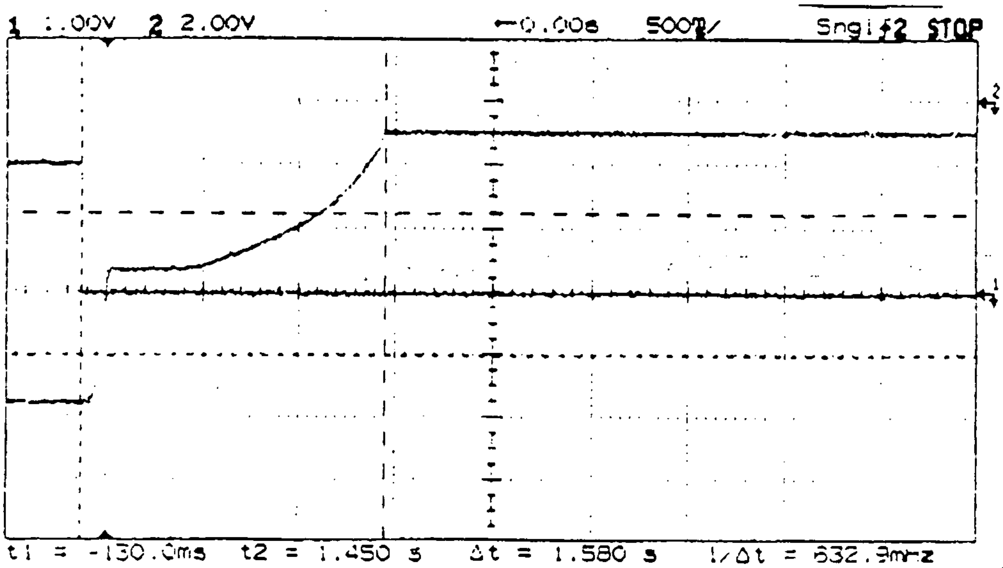
Date SEP 1 5 1992 Operator HRT 148

Serial No. X001

Comments: LOADED

Item		Required	Actual
Pneumatic Pressure, psig		695 ± 10	695
Starting Encoder, bits*	MPVA	2185 to 2196	2171
		2168 to 2179	
Ending Encoder, bits*	MPVA	256 to 299	253
		253 to 276	
Shutdown Time, sec		1.17 to 2.27	1.58

* Cross out non-applicable line.



tdown

RVDT #1
Demodulated
Output

2VDC/div

.5 sec/div
for MPVA

1.0 sec/div
for MFVA

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DOCUMENT NO. HR77700072

P/N X41009110

FAIL-OPERATE PERFORMANCE (ATP Para 4.11)

Date SEP 1 5 1992 Operator HRT 148

Serial No. X001

Comments: Loaded

Item	Required	Actual
# 1 Input	+ 24 M amp	+24
# 2 Input	-24 M amp	-24
Fail-Op Energized	20 M amp	20
Failsafe Energized	20 M amp	20
Ending Encoder Reading		777
Starting Encoder Reading		758
Diff. = Uncontrolled Actuator Travel	78 bits max.	19

Encoder Reading @ Travel Reversal: 777 Bits

Encoder Reading @ Fail-Op Energized: 758 Bits

Δ Position = Uncontrolled Actuator Travel: 19 Bits

FUTURE TEST PLANS

FUNCTIONAL

- FREQUENCY RESPONSE
- RATED LOAD/VELOCITY
- LINEARITY
- STABILITY
- PERFORMANCE

ENVIRONMENTAL

- VIBRATION/SHOCK
- EMI/EMC

FLIGHT SIMULATION LABORATORY

- REDUNDANCY
- FAULT INJECTIONS
- ENGINE SIMULATIONS (HARDWARE IN-THE-LOOP)

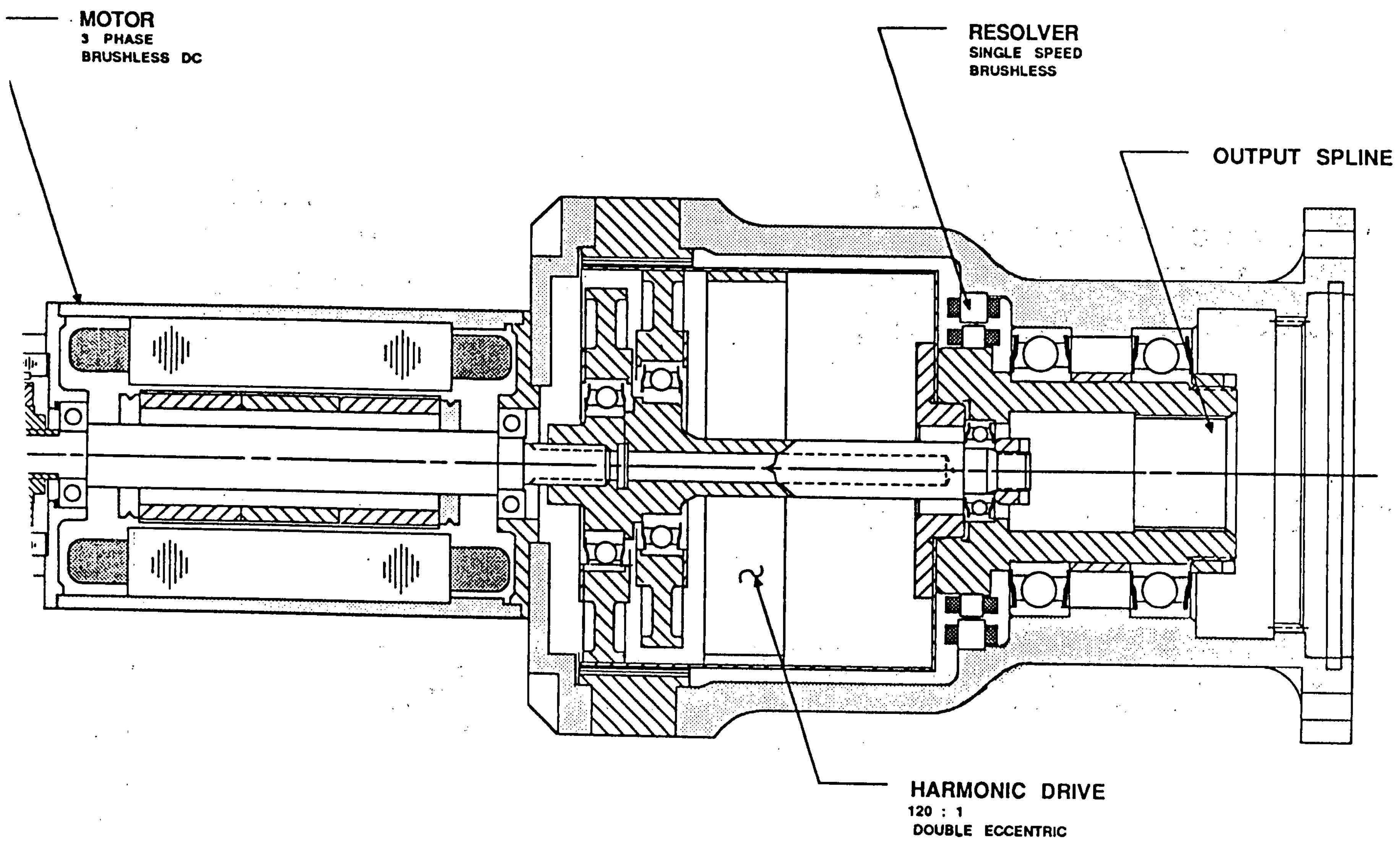
FLOW

- WATER FLOW/CRYOGENICS WITH MOV

TTB

- ENGINE HOT FIRE

SSME ELECTROMECHANICAL VALVE ACTUATOR



EMA DESIGN GROUPS

MECHANICAL

Propulsion Laboratory
Control Mechanisms &
Propellant Delivery Branch
(EP64)

ELECTRONIC CONTROLLER

Information & Electronics
Systems Laboratory
Control Electronics Branch
(EB24)

ELECTROMECHANICAL PROPELLANT CONTROL SYSTEM ACTUATOR

- DESIGN
  - MECHANICAL
  - ELECTRONICS/CONTROLLER
- TESTING
  - STATUS
- FUTURE PLANS

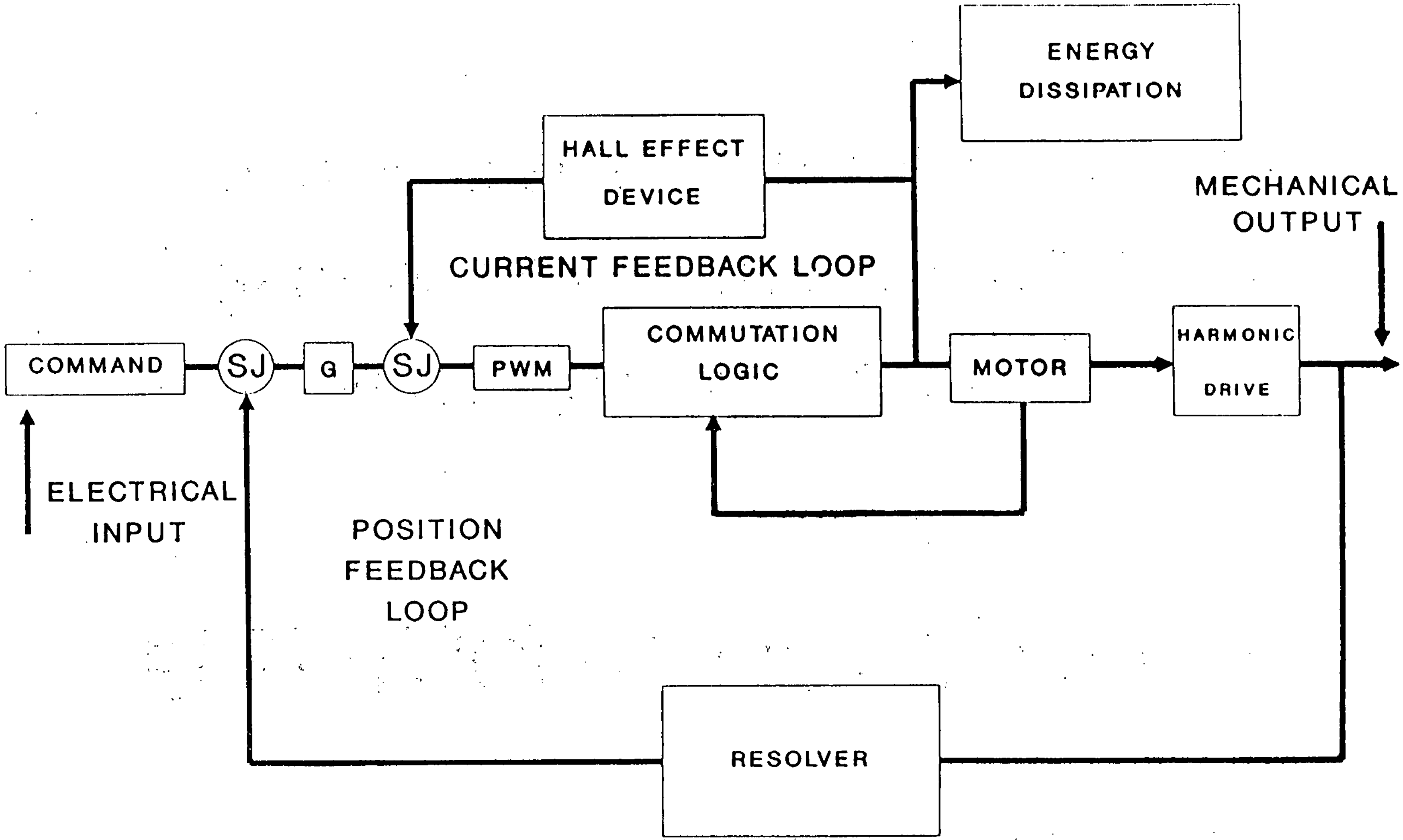
MECHANICAL COMPONENTS

- Motor
- Harmonic Drive
- Resolver
- Output Spline

ELECTRONIC CONTROLLER

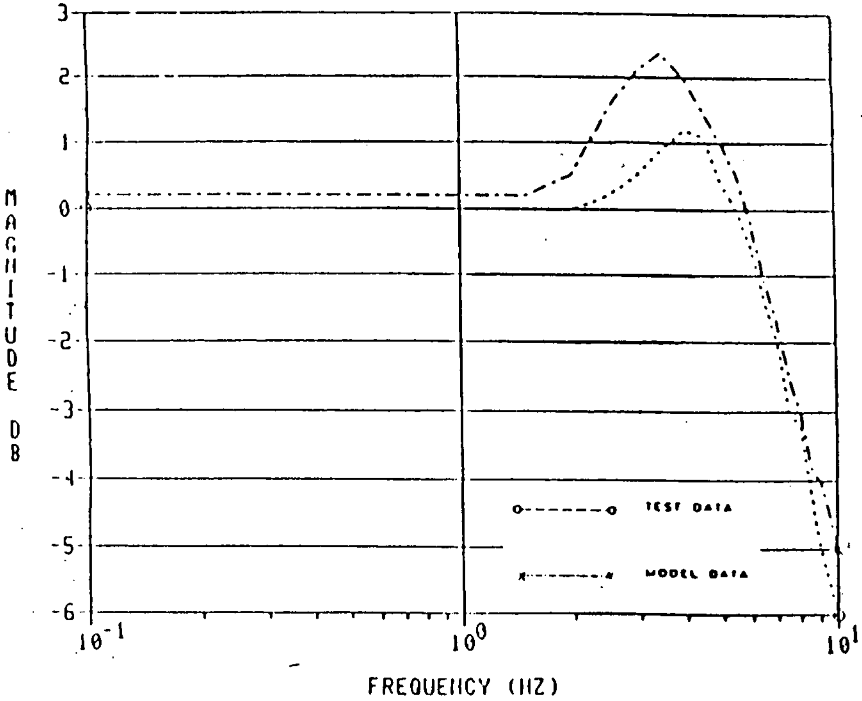
- PROVIDES CONTROL TO MOTOR
- PROVIDES EXCITATION TO RESOLVER
- CONTAINS ENERGY DISSIPATING DEVICE

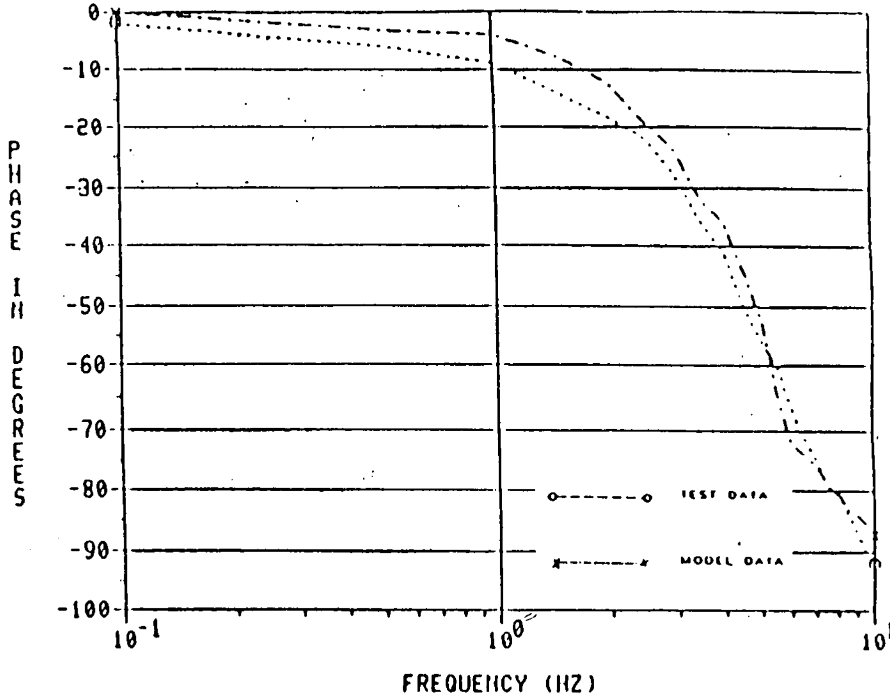
CONTROLLER BLOCK DIAGRAM



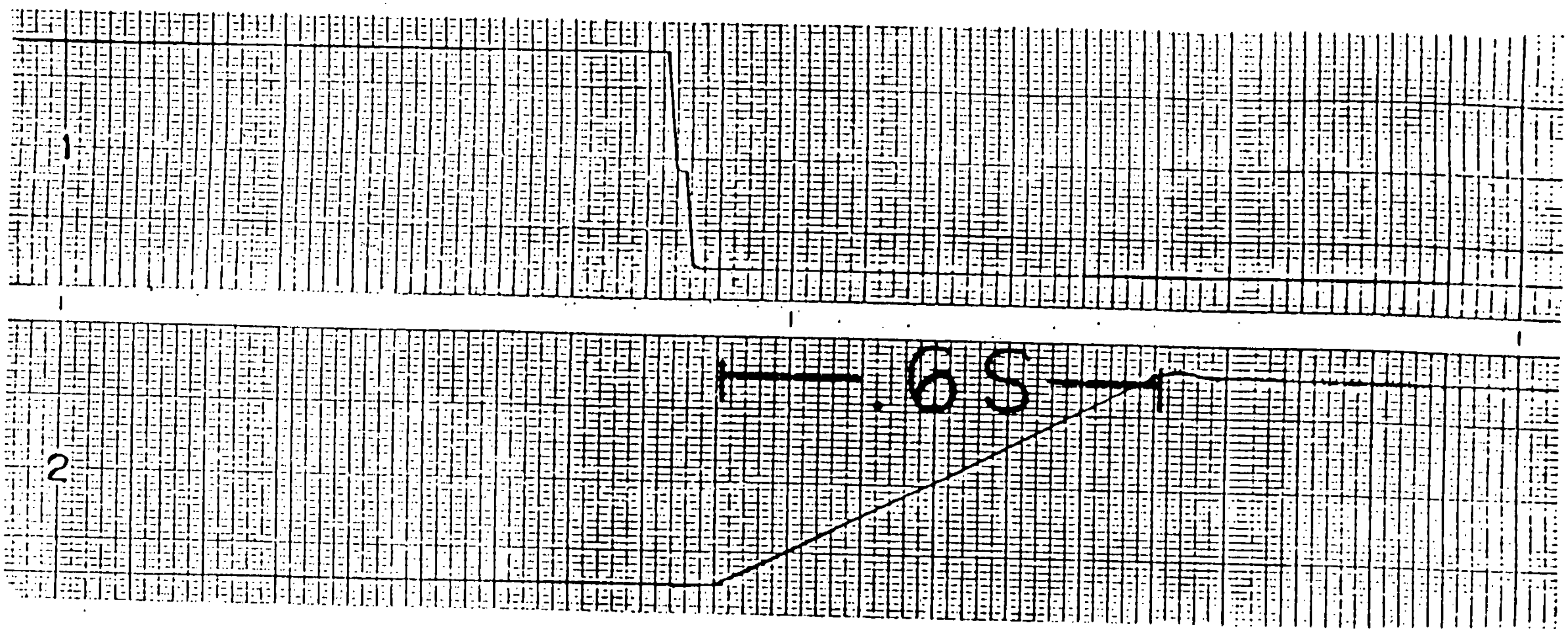
TESTING

- Developed and Verified Model
- Unloaded Testing
  - Frequency Response
  - Velocity
- Loaded Testing
  - Frequency Response





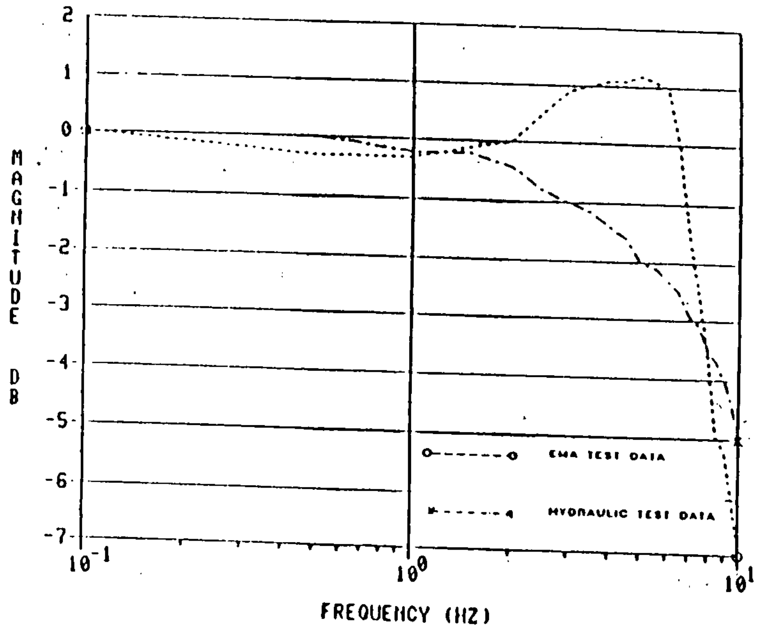
MODEL AND EMA FREQUENCY RESPONSE TESTS

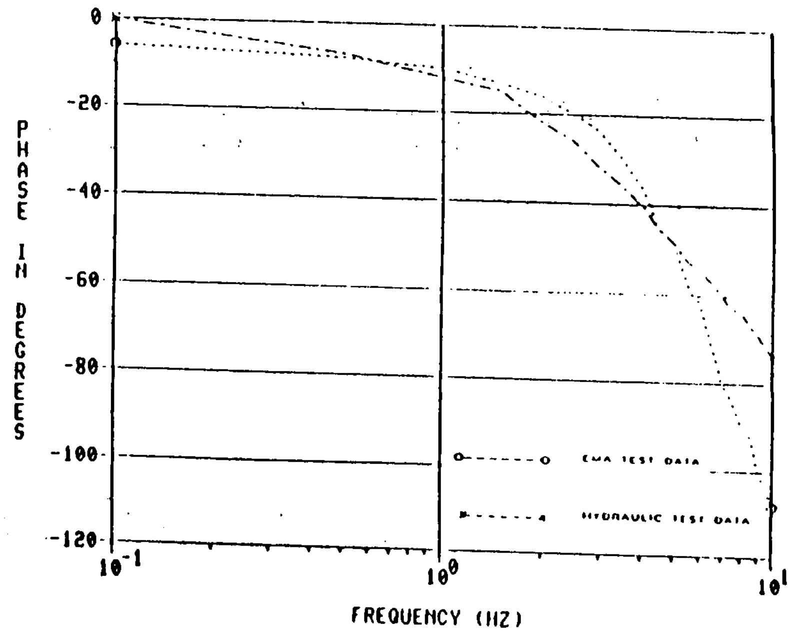


EMA NO-LOAD VELOCITY TEST

EQUIPMENT NEEDED TO COMPLETE TESTING

- 4000 Watt Controller
- Valve Simulator





HYDRAULIC AND EMA FREQUENCY RESPONSE TESTS

FUTURE TEST PLANS

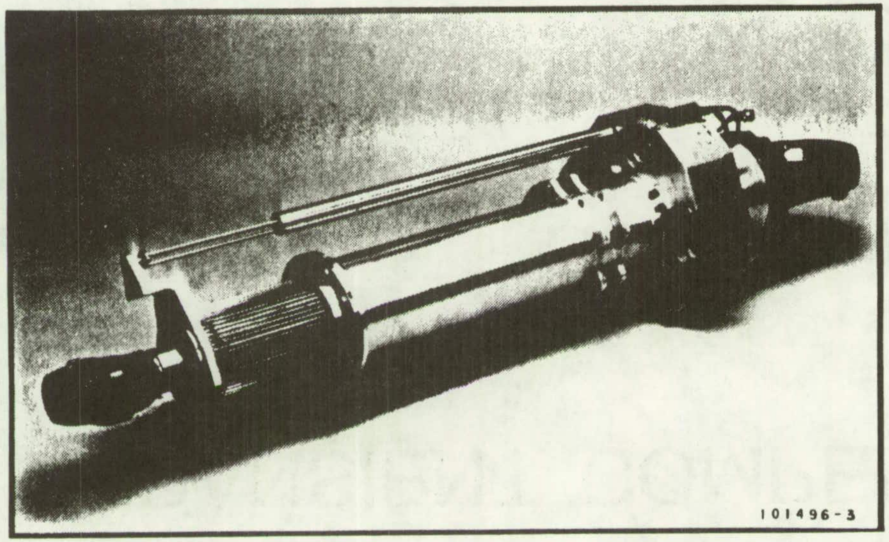
- Steady State Position Accuracy
- Temperature Tests
- Vibration Tests
- Comparison Between EMA And Hydraulic

TRANSIENT COMPENSATION EMA

Bill Fellows

September 29, 1992

ALLIED-SIGNAL RESEARCH
ELECTROMECHANICAL ACTUATOR (EMA)



SPECIFICATIONS

TRIPLE 11HP MOTORS	
POWER:	270 VDC
FORCE:	35,000 LB
TRAVEL:	10 INCHES
TRAVEL TIME:	2 SECS
BANDWIDTH:	13 HZ
WEIGHT:	102 LB
LENGTH: (EXTENDED)	46 INCHES

FEATURES

- REPLACES HYDRAULIC ACTUATORS
- FAULT TOLERANT ELECTRONICS
- BUILT-IN TEST CAPABILITY
- RATE AND POSITION COMMANDS
- FORM AND FIT COMPATIBLE WITH HYDRAULIC ACTUATORS
- HIGH EFFICIENCY

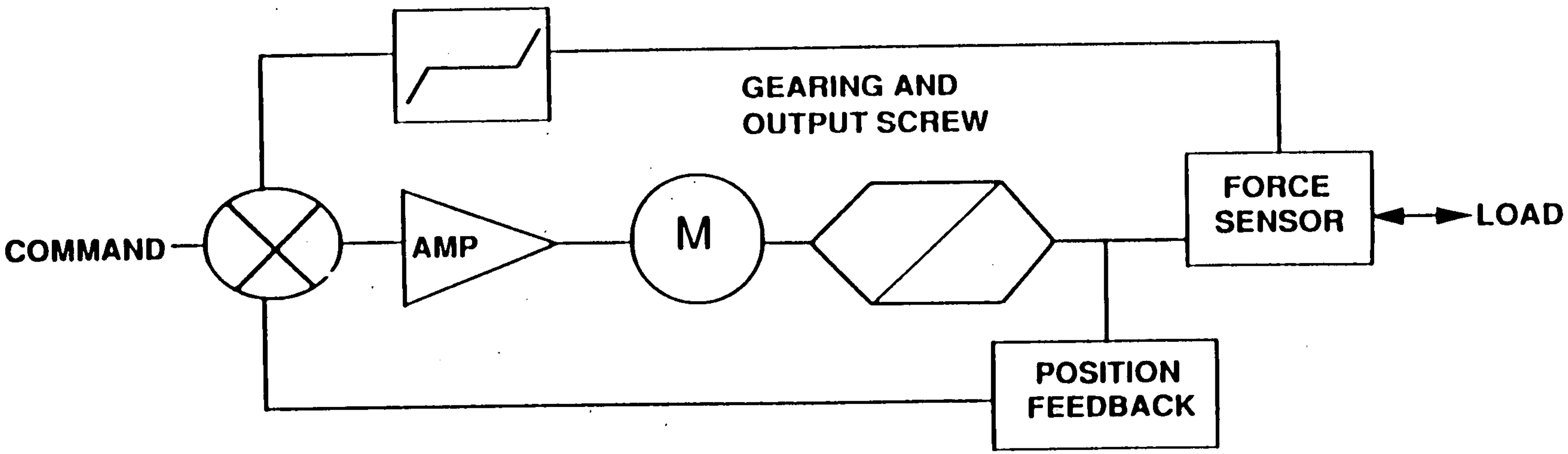
M-00280

SYSTEM DESCRIPTION

FOR THE PURPOSE OF MODELING, A SYSTEM COMPRISED OF TWO ALLIED-SIGNAL F20 MOTORS WAS UTILIZED. THIS SYSTEM WILL MEET THE PERFORMANCE REQUIREMENTS OF THE TITAN IV FIRST STAGE. THE BLOCK DIAGRAM FOR THE SYSTEM IS SHOWN. THE REDUNDANCY ASPECTS OF HAVING TWO MOTORS IS NOT SHOWN - THE MOTORS ARE LUMPED INTO ONE FOR THIS STUDY. THE GEAR RATIO IS APPROXIMATELY 37:1 INTO A 0.625 LEAD BALLSCREW, FOR AN OVERALL GEAR RATIO OF 5400:1. THIS PROVIDES A 30,000 LB. OUTPUT OF THE ACTUATOR AT 3.5 IN-SEC. THE LIMIT LOAD OR STRUCTURAL CAPACITY OF THE ACTUATOR IS ASSUMED TO BE 60,000 LBS. MINIMUM, WHICH IS AT LEAST TWICE THE RATED OUTPUT. THE FORCE FEEDBACK INTO THE CONTROLLER HAS AN ELECTRICAL BIAS OF 40,000 LBS.

EM TVC TRANSIENT LOAD COMPENSATION

- IF THE REACTED FORCE ON THE ACTUATOR IS INSTRUMENTED, IT MAY BE FED BACK TO THE SERVO LOOP TO CAUSE A REDUCTION IN STIFFNESS WHEN THE LOAD TRIES TO EXCEED THE RATED LOAD

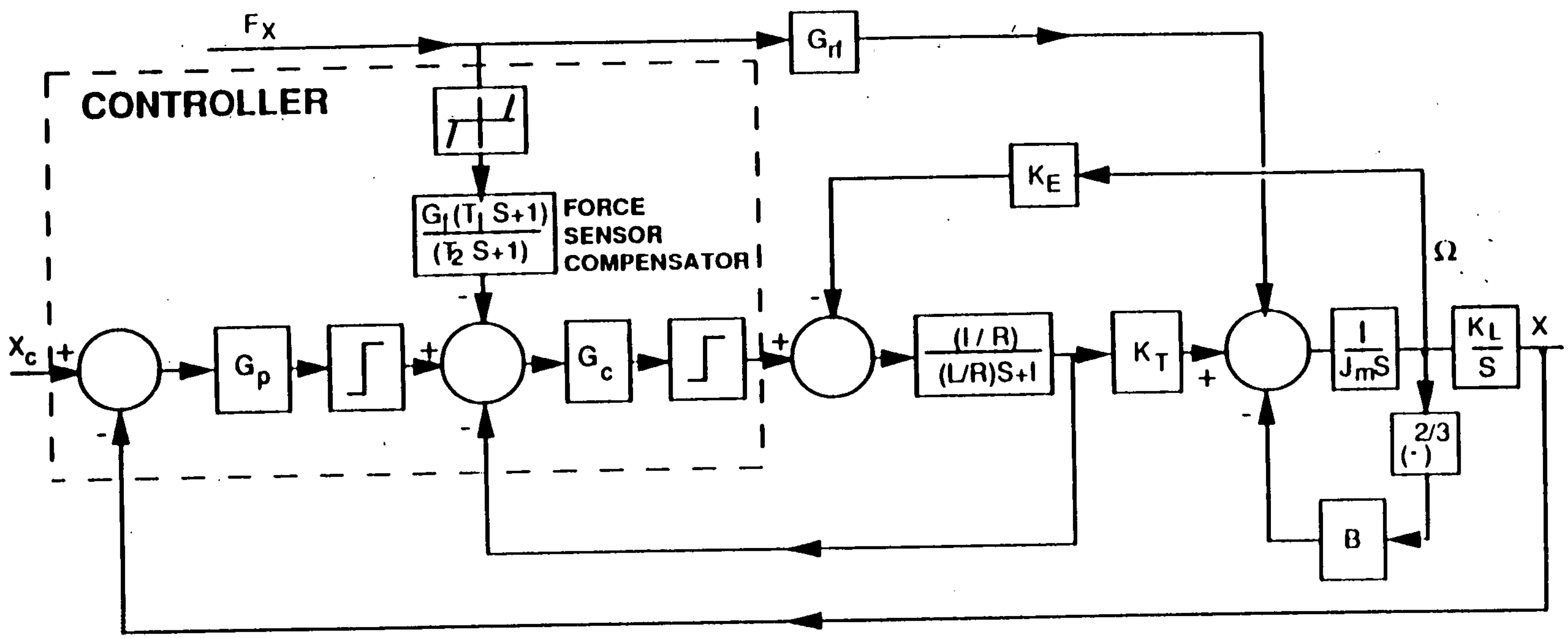


GENERAL DESCRIPTION OF ACTIVE COMPENSATION

THE BASIC PHILOSOPHY OF THE COMPENSATION IS TO DETECT THE APPLIED LOAD AND WHEN IT IS GOING TO EXCEED THE MAXIMUM ACTUATOR REQUIRED OUTPUT USE THIS LOAD TERM TO CAUSE THE ACTUATOR TO BACK AWAY FROM THE EXCESS TRANSIENT. THE RESPONSE OF THE TVC SYSTEM WHILE OPERATING UNDER NORMAL LOADS DOES NOT HAVE TO BE AS HIGH AS THE TRANSIENT LOAD. IN NORMAL OPERATION, THE ENGINE INERTIA AND LOADS HAVE A SIGNIFICANT EFFECT ON THE ACTUATOR RESPONSE CAPABILITIES. WHEN REACTING TO A TRANSIENT LOAD, THE ENGINE INERTIA IS THE MOVER AND THE RESPONSE CAPABILITY OF THE ACTUATOR TO MOVE OUT OF THE WAY IS THE RESPONSE OF THE ACTUATOR MOTOR ALONE, I.E., THE MOTOR MUST ACCELERATE WITH THE HELP OF AN AIDING LOAD. THIS MEANS THAT A SYSTEM WITH AN OPERATIONAL FREQUENCY RESPONSE OF 4 Hz MAY HAVE NO PROBLEM COMPENSATING FOR A 15 Hz TRANSIENT LOAD.

AS AN EXAMPLE OF THE ABOVE, A PRELIMINARY SIZING INDICATES THAT A TVC ACTUATOR USING TWO ALLIED-SIGNAL F20 BRUSHLESS DC MOTORS WILL MEET THE PERFORMANCE REQUIREMENTS OF TITAN IV. WHEN IN NORMAL OPERATION AND MOVING THE TITAN IV ENGINE, THE FREQUENCY RESPONSE IS IN THE ORDER OF 7 OR 8 Hz. THE RESPONSE CAPABILITY WHEN REACTING TO A TRANSIENT LOAD IS IN THE ORDER OF 19 Hz. THIS IS COMPATIBLE WITH REQUIREMENTS FOR COMPENSATING A 12 Hz TRANSIENT INPUT.

EM TRANSIENT LOAD COMPENSATION MODEL



NOMENCLATURE

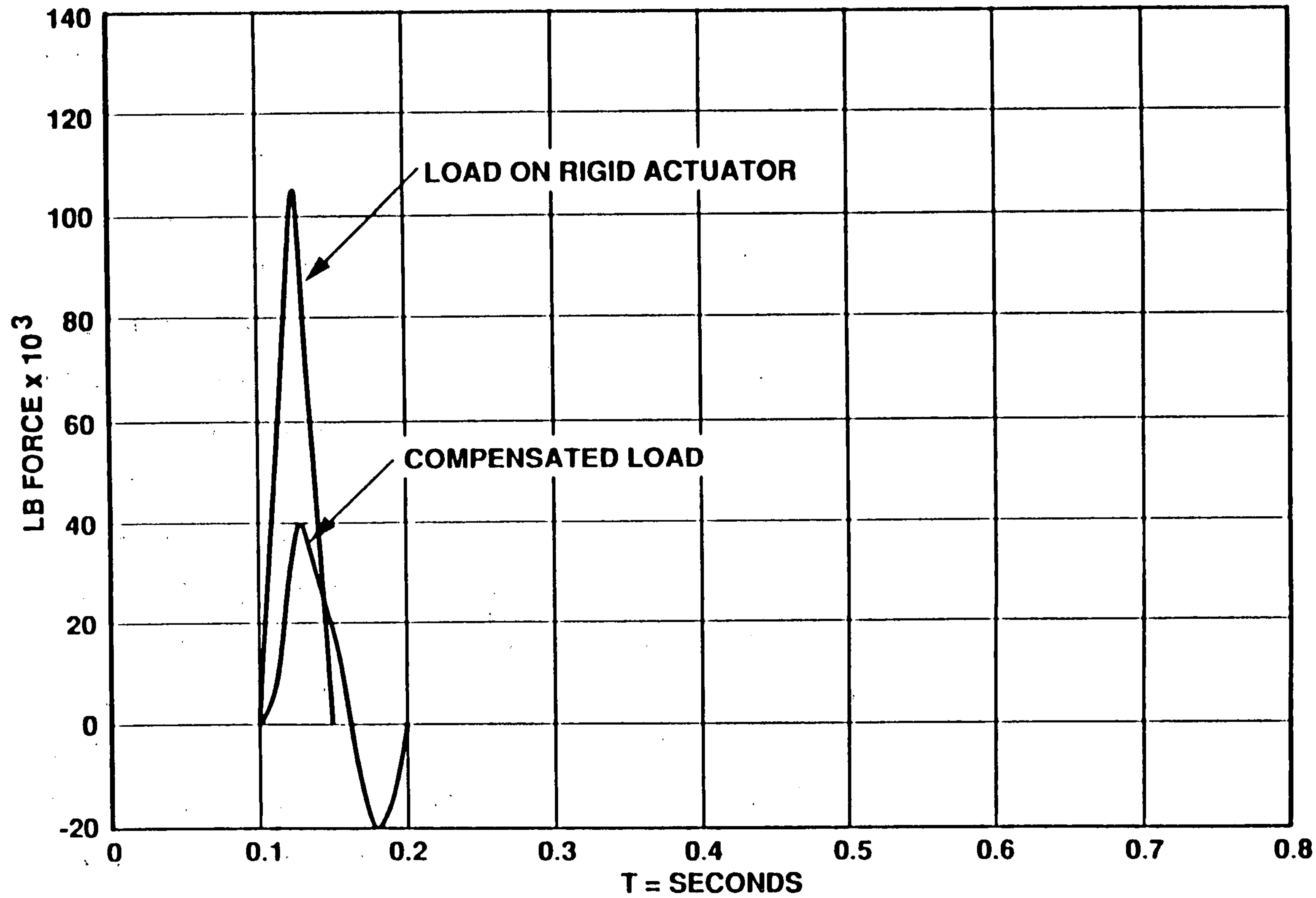
F_x	LOAD	J_m	MOTOR POLAR MOMENT OF INERTIA
X_c	POSITION COMMAND	K_L	COMBINED GEAR RATIO
X	ACTUAL POSITION	K_T	TORQUE CONSTANT
K_E	BACK EMF CONSTANT	I_m	MOTOR CURRENT
Ω	MOTOR SPEED	G_p, G_c, G_l	GAIN CONSTANTS
R	RESISTANCE	T_1, T_2	LEAD COMPENSATOR TIME CONSTANTS
L	INDUCTANCE		

Allied-Signal Aerospace Company

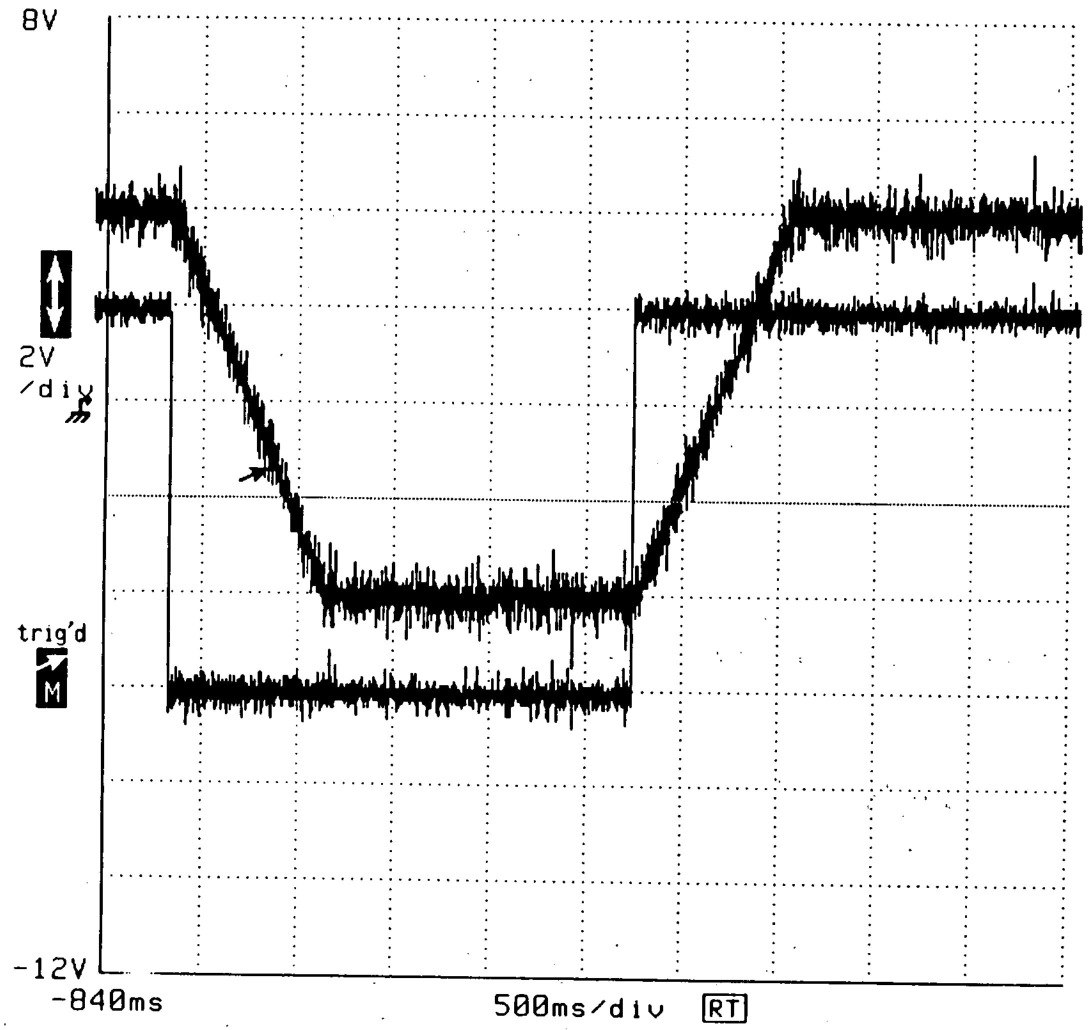
AlliedSignal

MODEL AND RESULTS

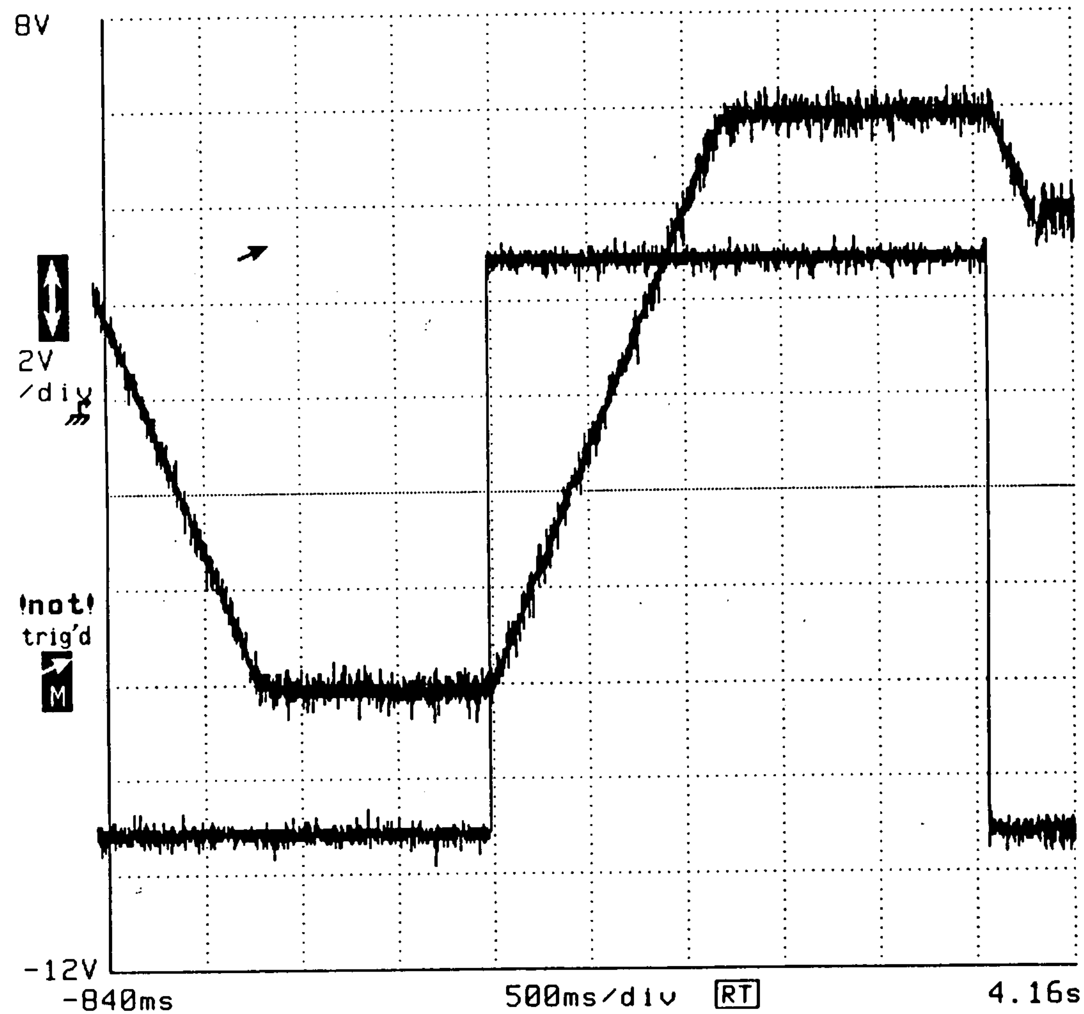
USING THE SYSTEM DESCRIBED, A 12 Hz TRANSIENT WAS APPLIED WHICH HAD A PEAK UNCOMPENSATED FORCE OF 105,000 LBS. THIS LEVEL WAS SELECTED HIGH BECAUSE COMPLETE DATA ON THE TRANSIENT CHARACTERISTICS ARE NOT AVAILABLE. FOR COMPARISON, TWO ENERGY LEVELS OF TRANSIENTS WERE USED: A 1500 IN-LB. AND A 7500 IN-LB. THE CONTROLLER IN THE MODEL HAS A 40,000 LB. DEADBAND WHICH IS 10,000 LBS. OVER THE RATED OUTPUT. THIS MEANS THAT UNDER STATIC CONDITIONS, THE ACTUATOR WILL BE RIGID FOR ANY LOADS UNDER 40,000 LBS. THE REACTION AND RESULTS OF THE MODELED SYSTEM TO THE 1500 IN-LB. LEVEL IS SHOWN. THE ABILITY OF THE SYSTEM TO REDUCE THE LOAD AT THE 7500 IN-LB. LEVEL IS LIMITED BY THE SPEED LIMITATION OF THE ACTUATOR, NOT ITS FREQUENCY RESPONSE. IN OTHER WORDS, IT CANNOT MOVE ENOUGH DISTANCE IN THE TIME TO FURTHER REDUCE THE TRANSIENT. EVEN WITH THIS LIMITATION, THE LOAD WAS REDUCED FROM ABOUT 105,000 LBS. TO 55,000 LBS., WELL WITHIN THE STRUCTURAL LIMIT REQUIREMENTS. AT THE 1500 IN-LB. ENERGY LEVEL, THE FORCE WAS REDUCED TO 40,000 LBS. IN EITHER CASE, IT CAN BE SEEN THAT THE COMPENSATION SIGNIFICANTLY REDUCES THE PEAK LOAD TO WITHIN STRUCTURAL LIMITATIONS WHICH IS TAKEN TO BE 60,000 LBS.


140
120
100
80
60
40
20
0
-20
LB FORCE x 10^3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
T = SECONDS
LOAD ON RIGID ACTUATOR
COMPENSATED LOAD

NO LOAD STEP RESPONSE



MASS LOADED STEP RESPONSE
6600 POUNDS



Allied-Signal Aerospace Company

AiResearch Los Angeles Division

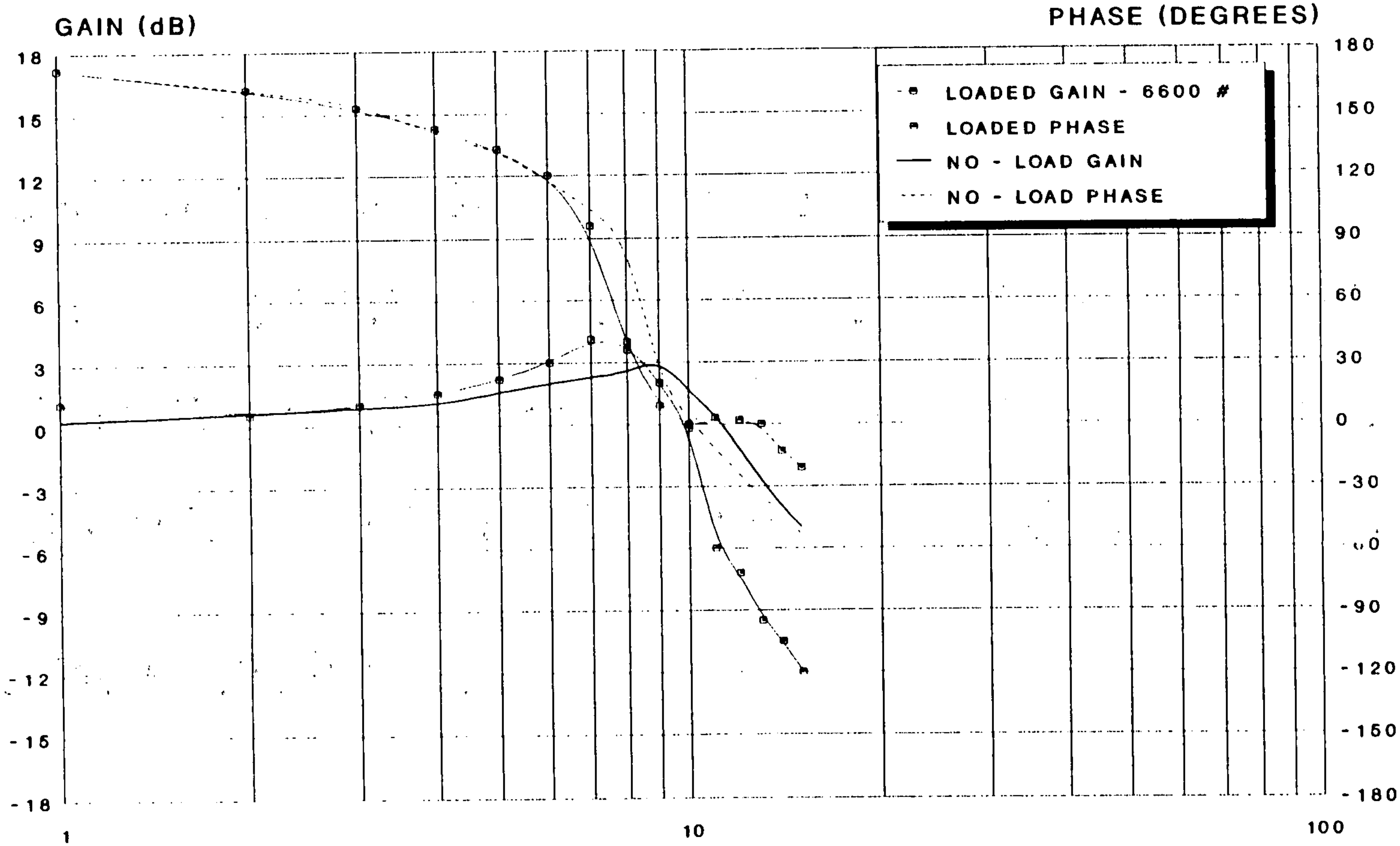
Allied Signal

FREQUENCY RESPONSE

THE FREQUENCY RESPONSE OF THE TEST UNIT WAS RUN BOTH UNLOADED AND WITH A 6600 LB. INERTIA LOAD. THE RESULTS SHOW THAT THE RESPONSE EXCEEDS 10 Hz IN BOTH CASES.

GAIN AND PHASE

6600 POUND LOAD AND NO - LOAD



LOG FREQUENCY (Hz)

SESSION XIII

DEMONSTRATION

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13. ABSTRACT *(Maximum 200 words)*

This document contains the proceedings of the NASA Electrical Actuation Technology Bridging (ELA-TB) Workshop held in Huntsville, Alabama, September 29–October 1, 1992. The workshop was sponsored by NASA Office of Space Systems Development and Marshall Space Flight Center (MSFC). The workshop addressed key technologies bridging the entire field of electrical actuation including systems methodology, control electronics, power source systems, reliability, maintainability, and vehicle health management with special emphasis on thrust vector control (TVC) applications on NASA launch vehicles. Speakers were drawn primarily from industry with participation from universities and government. In addition, prototype hardware demonstrations were held at the MSFC Propulsion Laboratory each afternoon. Splinter sessions held on the final day afforded the opportunity to discuss key issues and to provide overall recommendations. Presentations are included in this document.

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